Straight From The Cow's Mouth: Investigating procurement and management strategies in cattle supplied to Great Zimbabwe using a multi-isotopic approach

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Abstract

Great Zimbabwe was the centre of an ancient Shona state from AD1200- 1700. It is known for its magnificent architecture and involvement in long-distance (inter-continental) and local (inter-regional) trade. In this society, cattle were vitally important in social, economic and political spheres. However, the origins and herd management strategies of cattle from Great Zimbabwe have never been explored using empirical evidence, although researchers have proposed seasonal transhumance between upland and lowland regions. In this thesis, measurements of $^{87}Sr/^{86}Sr$, $\delta^{18}O$, $\delta^{13}C$ and $\delta^{15}N$ profiles in serial samples of tooth enamel and dentine from 27 archaeological cattle teeth enable investigation of several aspects of cattle procurement and management. Taken together, the isotope measurements show that cattle at Great Zimbabwe came from a broad geographical area. Some cattle were raised (for the first year of life) less than 40kms away from Great Zimbabwe, most were raised in the lowveld of the country between 40 and 120kms south of the site and some may have moved between the two areas. Cattle fed mainly on C_4 grass throughout the period from AD1300 to 1600, although some also consumed limited amounts of browse. Heterogenous $\delta^{13}C$ profiles indicate that animals derived from different environments, and that calves were born at different times of year. This study emphasises the advantages of using multiple isotopes to extract maximum information from archaeological tissues. In combination with the distribution of material culture, particularly from sites coeval with Great Zimbabwe, this study contributes to our understanding of the flow of key resources within the Zimbabwe state, enhancing knowledge of relationships between sites and regions. This study emphasises how economically connected the landscape was during the thriving of the Zimbabwe state. It makes a significant contribution to our hitherto very limited knowledge of the flow of regional (as opposed to imported) commodities. Future work should target lesser studied Zimbabwe-type sites in southern Zimbabwe to further explore interactions and relationships between hinterland sites and their centres.

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Chapter 1: Introduction

From around AD900, urban states[1] in southern Africa began to rise and flourish. This was accompanied by a network of resources flowing between the interior and the Indian Ocean region. One of the best-studied of these urban units is the Zimbabwe state which flourished from approximately AD1200 to 1700 (Garlake, 1973; Pikirayi, 2001; Chirikure et al., 2018a; Chirikure, 2019). The state imported goods such as glass beads, textiles and porcelain in exchange for local goods like copper, iron, gold, ivory and possibly ceramics.

It is difficult to establish the exact area of influence of the Zimbabwe state. Territories have been suggested to have stretched from the Indian Ocean (i.e. the coastline of present-day Mozambique) to the Kalahari Desert (in modern Botswana) (Garlake, 1973). However recent research shows that it is likely that there were several states functioning at the same time in a heterarchical landscape (Chirikure et al. 2013a, 2013b, 2018b)(Figure 1) making the bounds of the Zimbabwe state tricky to establish. The state centre or capital within the Zimbabwe state was Great Zimbabwe. It contains lavish drystone architecture across most of the site; the most intensively researched areas are the Hill Complex (Robinson, 1961; Chipunza, 1994), the Great Enclosure (Summers et al., 1961) and the Valley Enclosures (Collett et al., 1992). It also contains unwalled areas with midden deposits and house floors. In total, the site extends over approximately 720ha.

[1] There is no definition for a state which encompasses all variability, but a state can generally be defined as a form of social and political organisation where territories made up of administrative centres and supporting outland areas are controlled by rulers (Trigger, 2003). In this context, the Zimbabwe state is such a unit in which Great Zimbabwe was the administrative centre.

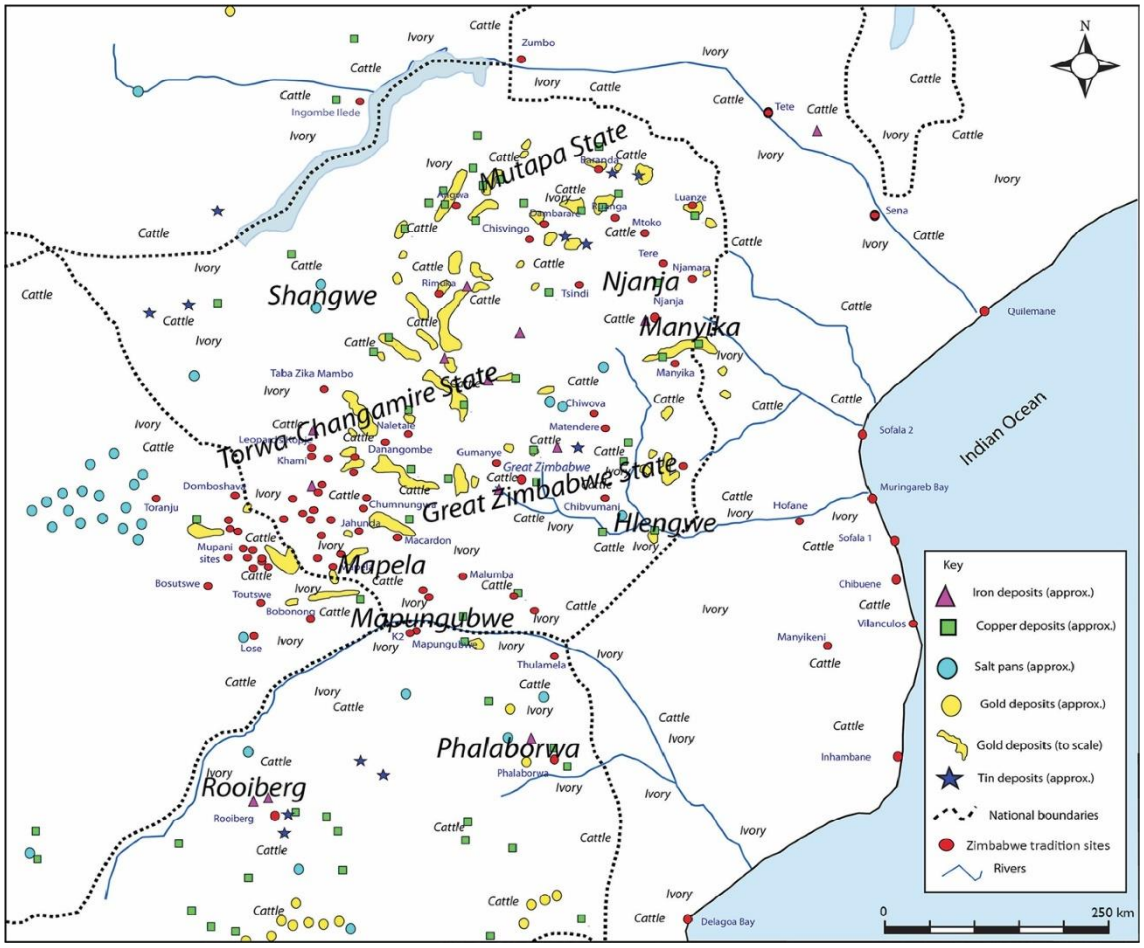


Figure 1: Polities which existed between the 13th and 17th centuries AD in Zimbabwe and northern South Africa (after Chirikure, 2019). Available regional resources listed in key. Well-known Iron Age sites marked in red

On the rediscovery of Great Zimbabwe by amateur Western archaeologists, it was considered that the site was built by foreign groups rather than locals (Bent, 1892; Hall, 1905). However, by the 1930s, chronological and material investigation by professional archaeologists proved that the site was local in origin (Randall-MacIver, 1906; Caton-Thompson, 1931; Summers, 1971; Garlake, 1973). The earliest occupation was by first millennium AD farmers. The most intensive occupation was from around AD1200 through to the historical period. The lavish drystone walling at the site was the focus of the most research (Whitty, 1961; Garlake, 1973; Chipunza, 1994; Pikirayi, 2013). The resultant hypotheses about the site were based on excavations in these walled areas in combination with Venda ethnographies and the study of Mapungubwe. Researchers proposed that elite groups were associated with hilltop settlements, exotic trade goods and areas of drystone walling whilst commoner groups were associated with local trade and occupations on flat unwalled areas (Huffman, 2007). This structural model was later challenged by excavations in unwalled areas which yielded material culture similar to that

from ‘elite’ areas of the site (Chirikure et al., 2018b). The hypothesis proposed on the basis of this new information was that centres of power within Great Zimbabwe shifted in rotational succession, resulting in elite objects being recovered in many areas of the site (Beach, 1998; Beach et al., 2007; Chirikure and Pikirayi, 2008; Chirikure et al., 2018b).

Investigations into the economy of Great Zimbabwe have focussed on the circulation of exotic trade goods (Caton-Thompson, 1931; Garlake, 1973; Huffman, 2009) rather than trade in local commodities such as cattle, salt, ceramics, gold and other metals. A consequence of this is that some hypotheses for the rise and decline and the ethnic stratification observed at the site have centred around the regulation of exotic trade goods (Huffman, 1972, 1996; Pikirayi, 2001, 2017). This also created a core-periphery economic system hypothesis where peripheral sites were seen as subordinate to the core at Great Zimbabwe (Huffman, 2007). As a result, a greater focus on the role of local trade commodities within the Zimbabwe state is greatly needed. Cattle formed an integral component in local trade (Garlake, 1978; Pikirayi, 2001; Chirikure, 2019) and provide the motivation for this study.

Cattle as well as crops such as millet and sorghum formed the subsistence base of these farming communities. Across the Zimbabwe state, cattle were a vital economic commodity for all levels of society: kings, chiefs and independent households alike (Garlake, 1978; Rudd, 1984; Manyanga, 2006). The primary function for cattle was to provide meat and milk, but their importance exceeded these bounds. Crucially, cattle also formed a key component in social practices, as a symbol of wealth, in bridewealth transactions and in forming links to the ancestors. The importance of cattle in the archaeological record is supported by the thousands of cattle bones excavated at early farming sites. These issues are covered in more detail in later chapters.

Given the social, economic and political importance of cattle in present-day Zimbabwe, combined with the importance of Great Zimbabwe as an early state, it is surprising that little is known about cattle management at the site. Lines of investigation have been limited to examining the age profiles of cattle from Great Zimbabwe and comparing them with those from smaller walled sites (Brain, 1974; Thorp, 1995; Reid, 1996; Chiripanhura, 2017). Research into cattle management has proposed that a seasonal transhumance strategy was implemented at Great Zimbabwe (Garlake, 1978). This is thought to have entailed the seasonal movement of livestock from the Zimbabwe plateau to pastures further afield, (Garlake, 1978; Sinclair, 1984, 1987) especially the good year-

round grazing in the lowveld of the country which would have been best used in winter, when tsetse-fly was less dangerous. This strategy would have enabled large herds to be maintained, while maximising nutrient intake by avoiding environmental degradation. This hypothesis has, however, never been tested empirically.

1.1 Research aims and objectives

Against this backdrop, this research uses serial isotopic analysis of cattle teeth excavated from several household areas of Great Zimbabwe to explore management and procurement strategies in cattle slaughtered at Great Zimbabwe.

Specific questions are:

- How much diversity was there in pasturing strategies in cattle supplied to Great Zimbabwe?

The heterogeneous nature of the vegetation around Great Zimbabwe and further afield means that stable carbon isotope ratios in serial samples of cattle tooth enamel and dentine will track C_3 browsing and C_4 grazing during the period of tooth growth. Similarities or differences in the patterns seen in different animals will provide information on possible diversity in pasturing strategies. Stable nitrogen isotopes can also inform on environmental conditions over the period of tooth formation.

- Was there more than one birth season in cattle supplied to Great Zimbabwe?

This question is addressed by comparing the trajectories of the stable carbon and oxygen isotopes from the occlusal surface of each tooth (which formed from birth) towards the cervix (for enamel) or root tip (for dentine). If the patterns of change in isotope values along the axis are all the same, then calves were probably born in one season. If they do not look the same, they probably weren't. Multiple birth seasons may indicate an attempt at building up herds to increase wealth or prestige.

- Was there seasonal movement of cattle herds (transhumance) across the landscape from the immediate vicinity of Great Zimbabwe to areas further away as proposed by previous researchers?

The measurement of $^{87}Sr/^{86}Sr$ may enable the identification of animals raised around Great Zimbabwe ($^{87}Sr/^{86}Sr$ values similar to local geology) and those which were not. Stable oxygen isotopes of cattle teeth, too, can provide information on the local hydrology in the area in which the animals were raised. The deliberate movement of cattle in southern Zimbabwe may give insight to the economic structure of the region and the relationship between Great Zimbabwe and smaller sites in surrounding areas.

- How widely across the landscape were cattle sourced for slaughter at Great Zimbabwe?

Based on $^{87}Sr/^{86}Sr$ values from the modern vegetation compared with that from the archaeological teeth, it may be possible to identify how far the cattle were being sourced and sent to Great Zimbabwe for slaughter.

1.2 Outline of thesis chapters

This thesis is organised as follows: Chapter Two provides an overview of the environment in which Great Zimbabwe is situated. The stable isotope composition of animal tissues depends strongly on environment. The environmental context will therefore be integral in interpreting the stable isotope results. This chapter then reviews the economy and the distribution of Zimbabwe-type sites in southern Zimbabwe and outlines the archaeology of Great Zimbabwe itself, describing the context of the materials used in this study.

Chapter Three reviews the significance of cattle in Shona societies based on modern ethnographies. The economic as well as the social role of cattle is discussed in detail. This provides motivation for why cattle specifically were selected for this study. The chapter then reviews contemporary cattle herding strategies used in southern Zimbabwe including seasonal use of forage, how herders cope with drought and tsetse fly and how cattle are incorporated into a broader mixed farming economy. This information can be used to generate scenarios to account for patterning seen in the stable isotope data, whilst

recognising social and landscape changes between the present and the archaeological past. Finally, gaps in research are presented.

Chapter Four describes the structure and formation of teeth, and the systematics of stable ($^{13}C/^{12}C$, $^{15}N/^{14}N$, $^{18}O/^{16}O$) and radiogenic ($^{87}Sr/^{86}Sr$) isotopes used in this study. It then reviews previous studies of animal husbandry practices based on stable isotope analyses of serially sampled teeth.

Chapter Five describes the materials and methods used in this study: the selection of teeth, laboratory pre-treatment and various isotopic analyses of each tissue.

Chapter Six reports the Results, and Chapter Seven discusses them and assesses how they contribute to our understanding of the Zimbabwe state.

Chapter 2: An overview of the study area: Great Zimbabwe

2.1 Introduction

Chapter Two describes the climate, geology and vegetation of the region around Great Zimbabwe. It then goes on to describe the subsistence economy in farming communities in southern Africa and the distribution of these sites within the Zimbabwe state. Finally, it outlines archaeological work done at Great Zimbabwe.

2.2 Climate, topography and vegetation of the study area

Great Zimbabwe is situated on gneissic rock formations and receives moderately high rainfall. Higher precipitation in the summer months leaches the acidic sandy soils, leading to the dominance of sourveld grass which is poor in nutrients during the dry winter season (Acocks, 1988). Some annual sweetveld grasses, too, occur in this area. This section outlines the major climatic, topographic and vegetation features of the study area which directly influence decisions by herders on seasonal pasturage[2] for their livestock.

2.2.1 Climate and hydrology

Based on variables such as amount of rainfall, temperature and soil type, Zimbabwe is divided into five Natural Regions which relate to modern agro-ecological capacity (see Table 2.1) (Vincent, 1961). Great Zimbabwe is in Natural Region III which is considered suitable for semi-intensive farming. The region is a tropical summer rainfall zone, with distinct hot-dry (September to November), hot-wet (December to March) and cool-dry (April to August) seasons. Great Zimbabwe is in a distinct rainfall zone relative to the surrounding areas and receives between 1000 to 1200mm of precipitation per annum (Figure 2.1). This is a considerably larger amount than surrounding areas, which receive some 500 to 700mm per annum (The Department of Meteorological Services, 1984). The reason for this is that Great Zimbabwe is located on the edge of the Zimbabwe plateau, at

[2] In this thesis 'pastured' is used as a general term to include consumption of both browse and graze. 'Grazing' refers to consumption of grasses (which in this environment are C_4), and 'browsing' refers to consumption of C_3 trees, bushes and shrubs.

a higher altitude than lower lying areas in the south of the country. Intermittent drought periods experienced in the last 20 years in the region have, however, reduced annual rainfall to approximately 700mm in recent years (Table 2.1). The largest amount of rain falls in December and the lowest in June (Bannerman, 1982; Manyanga, 2006). Sporadic rain may fall in the spring (September to November) known as *gukurahundi*. This is also the season when trees sprout new leaves (Manyanga, 2006).

The prevailing winds arriving at Great Zimbabwe are easterlies originating from the Mozambique channel. By the time they reach the site, they have travelled considerable distances over dry land and lost much moisture. However, as the winds reach the higher altitude Zimbabwe plateau and are forced to rise, the temperature decreases to dew point, the moisture in the air condenses to form clouds and light drizzle may fall. This is commonly known as *guti* (Manyanga, 2006). As a result of this, Great Zimbabwe receives more precipitation from different moisture sources compared with the lower-lying regions to the south. Stable oxygen isotopes vary with rainfall intensity as well as altitude. These differences are incorporated into animal tissues through the water they drink. They may be detected in the cattle tooth enamel and used to answer the research questions posed in Chapter One. These principles are discussed in detail in section 4.3.4.

As a result of the high altitude (1100m), the average temperatures at Great Zimbabwe are cooler than those in surrounding lower altitude areas. For the period from 1951-2002, temperatures for the summer months (November to February) averaged 22.5°C while those in winter (June to August), averaged 14.5°C (Simba et al., 2012).

Table 2.1: Climate and ecology associated with Natural regions in Zimbabwe (data taken from Manyanga (2006)

Region	**Mean Annual Rainfall (mm)**	**Mean Annual Temperature (°C)**	**Topography**	**Vegetation**	**Usage**
I	1000	18	Highlands	Montane Forest	Specialised
II	700-1050	18-19	Subdued relief	Miombo Woodland	Intensive
III	560-700	18-21	Undulating	Mixed Woodland	Semi-Intensive
IV	400-600	19-21	Broken	Deciduous woodland	Semi-Extensive
V	500	21-29	Flat/Broken	Mopane	Extensive

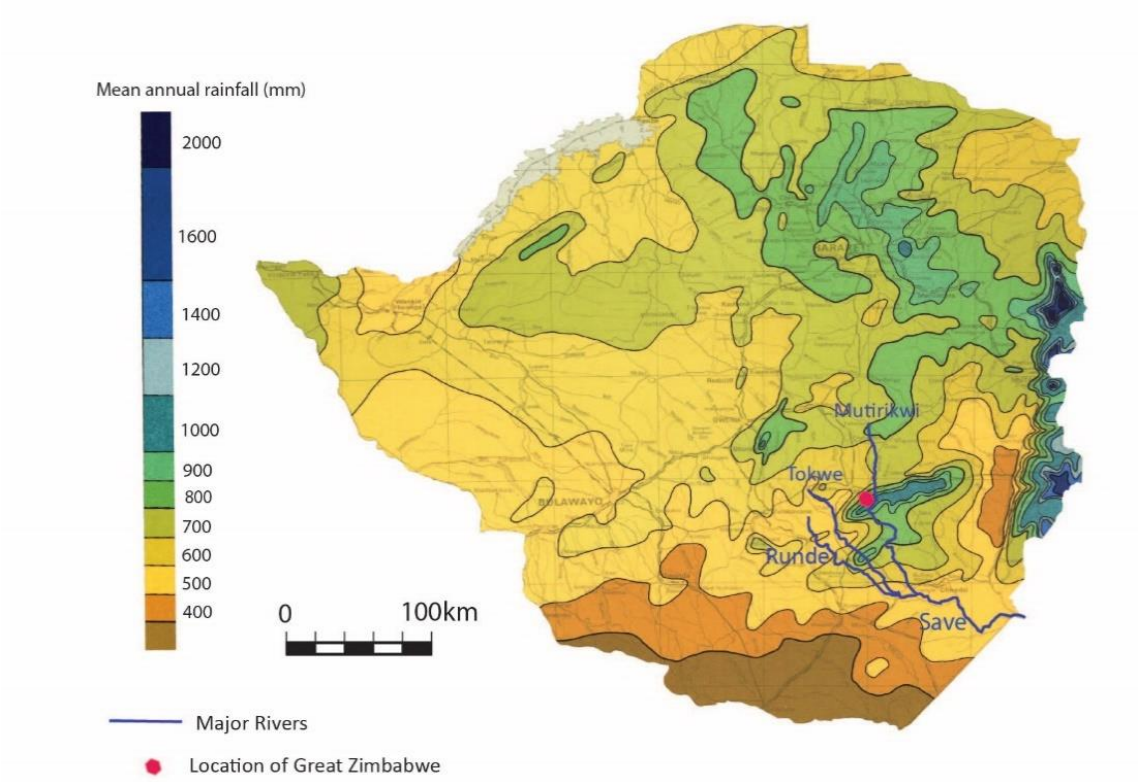


Figure 2.1: Precipitation map of Zimbabwe (adapted from (The Department of Meteorological Services, Zimbabwe. 1984)

The major rivers around Great Zimbabwe are the Runde and Tokwe rivers to the west and the Mutirikwi river to the east (see Figure 2.1). Small annual rivers flow during the summer rains. Other major water sources around Great Zimbabwe are seasonally waterlogged patches in low-lying treeless areas which are known locally as dambos. They are replenished either by direct precipitation or sub-surface through-flow from inter-fluves (Pikirayi et al., 2016). In pre-colonial Africa, dambos were an important source of water for farmers (Scoones, 1991).

2.2.2 Geology and Soils

The geology of southern Zimbabwe is complex and heterogenous. There are considerable areas of Precambrian geological formations with the basement complex containing granites, basalts, schists and metamorphosed lavas or greenstones as old as 2000 million years (see Figure 2.2). The dominant rock formations are intrusive igneous rocks for example granites and gneissic types. In the immediate vicinity of Great Zimbabwe, younger intrusive granites exist alongside older granites to the south and north-east of the

site (shown in pink, Figure 2.2). Further to the south and off the Zimbabwe plateau, Late Precambrian gneisses contain intrusions of early Precambrian metavolcanics and metasediments (shown in grey and olive green, Figure 2.2). Even further to the south, a belt of Karoo group basaltic formations dates to the Jurassic/Triassic Periods (shown in blue, Figure 2.2).

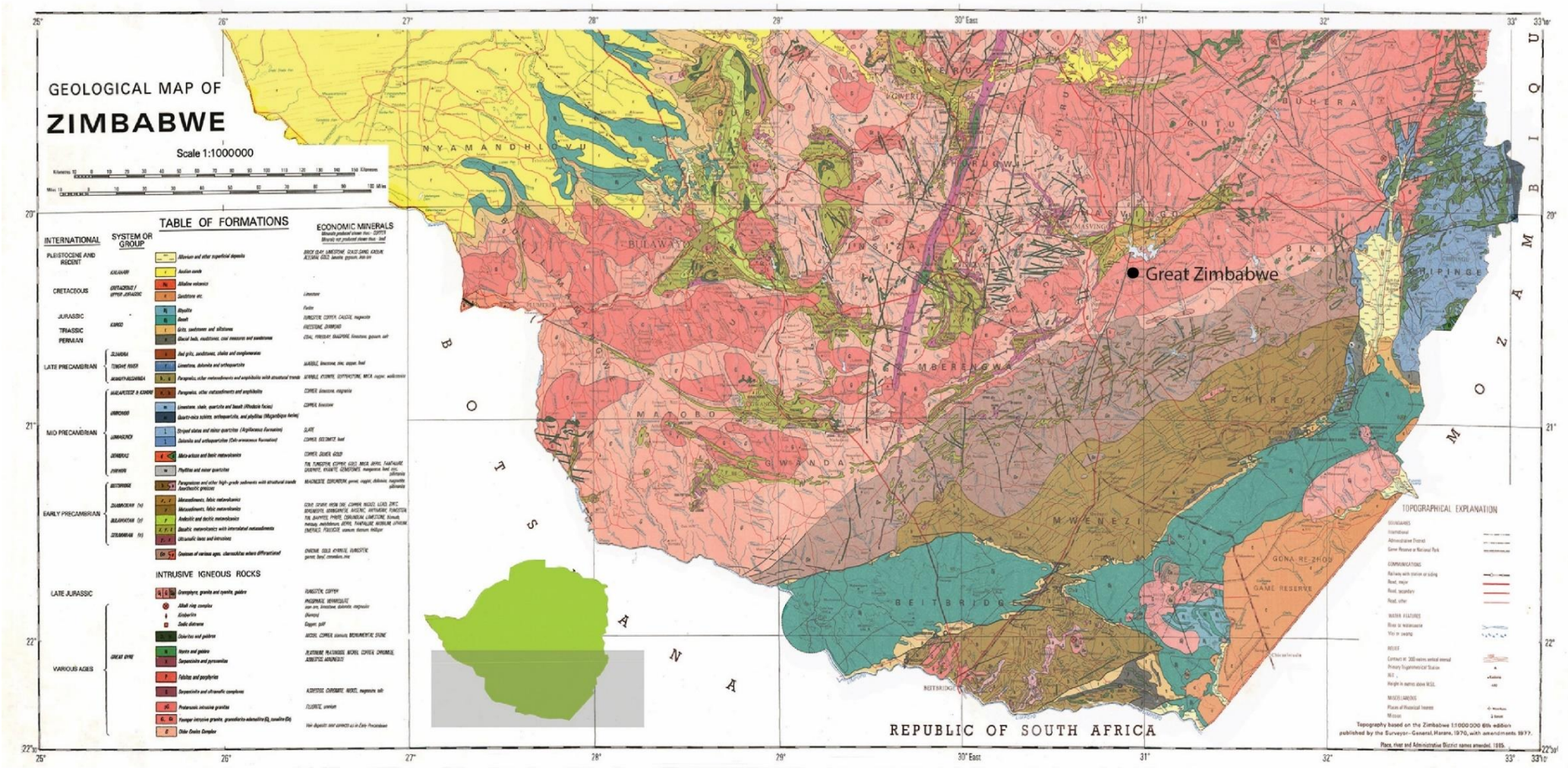


Figure 2.2: Geological map of Zimbabwe (adapted from Zimbabwe 1: 1 000 000 6th Edition published by the Surveyor-General, Harare, 1970, with amendments 1977).

Two main soil types dominate the area around Great Zimbabwe. The first are coarse to medium clayey loams which result from the weathering of basic igneous formations, greenstones and dolerites (Sinclair, 1987). They are fertile and rich in organic material (Floyd, 1959). The second are sandy soils which form from the weathering of granites, gneissic and paragneissic and sedimentary sandstones (Sinclair, 1987). These soils have low fertility and are poor in humics.

2.2.3 Vegetation

Savanna ecosystems are a major global terrestrial biome that include both grass and dispersed woody vegetation. Trees are scattered so they do not form a canopy, allowing sunlight to reach the ground between them (Beerling and Osborne, 2006). Savanna grasslands have been widely studied in southern African biomes and can broadly be separated into three groups based on climate, parent geology and soil nutrients (Ellery et al., 1995). These are sweetveld, mixedveld and sourveld grasslands. Sweetveld grasslands consist mainly of annual grasses in areas with low precipitation, low altitude and basic soils (derived from basalts and dolerites). Sourveld grasslands are dominated by perennial grasses in areas of high precipitation, high altitude and acidic soils (derived from quartzites and sandstone). Mixedveld occurs in intermediate zones (Tainton, 1981; Ellery et al., 1995).

There are three main types of savanna environments situated in and around Great Zimbabwe. In the immediate vicinity, one can find dry savanna woodland type vegetation with a mix of perennial sourveld and annual sweetveld grasses (shown in olive green in Figure 2.3). This includes *Brachystegia* or miombo woodland which covers the hillsides and the valleys surrounding the site (Sinclair, 1987; Chikumbirike et al., 2016; Pikirayi et al., 2016). A few kilometres to the north and south, there is an abundance of moist savanna woodland (light green in Figure 2.3) containing fine-leafed vegetation and annual sweetveld vegetation on relatively infertile soils. Farther south, one finds sweetveld mopane woodland and scrub savanna containing broad-leafed vegetation, particularly *Colophospermum mopane,* on semi-arid, fertile soils (yellow shades in Figure 2.3). The area around Great Zimbabwe is particularly interesting in relation to cattle herd management strategies of the past and present,

because of the proximity to both mopane woodland and miombo woodland; each providing seasonally distinct nutrients for domesticates.

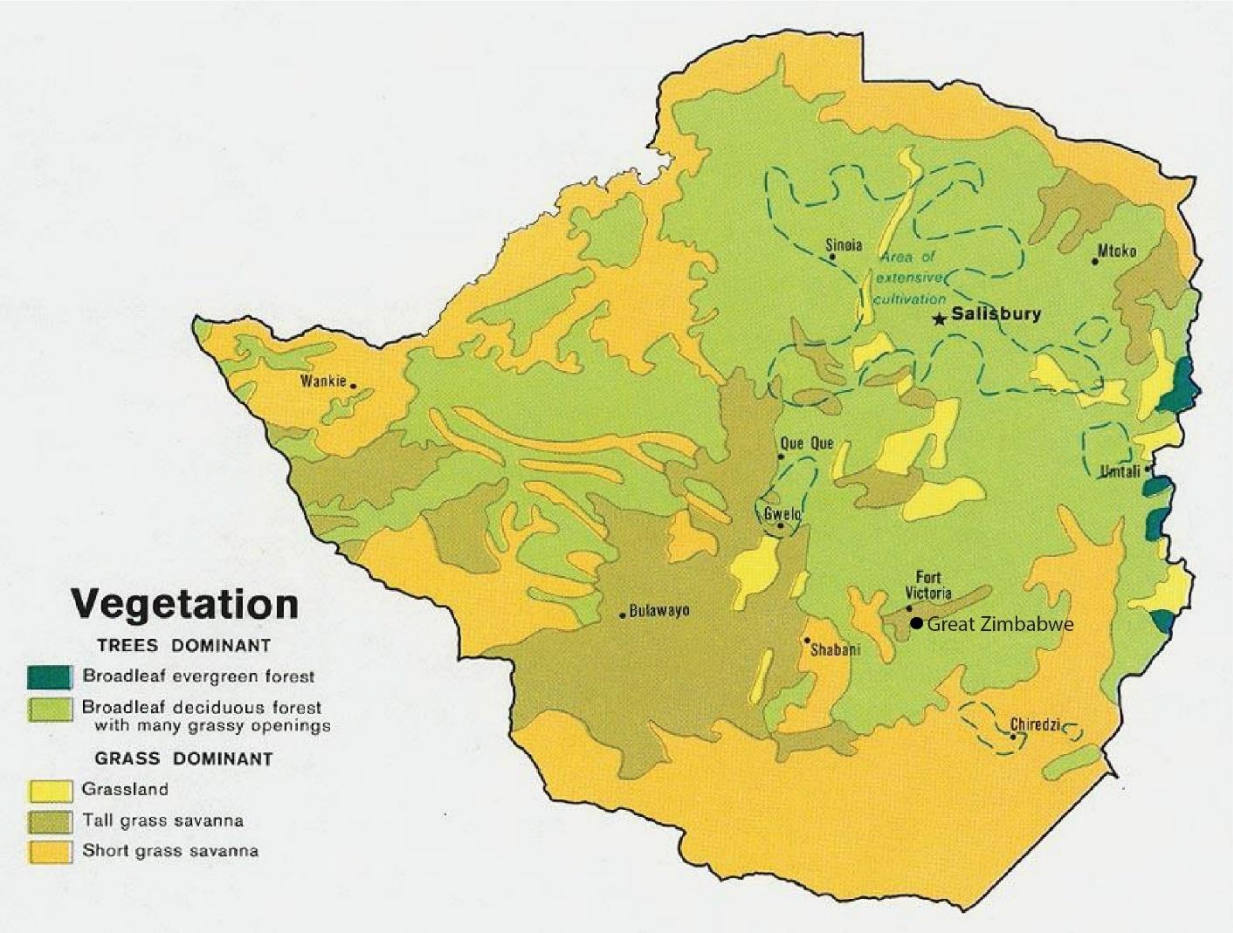


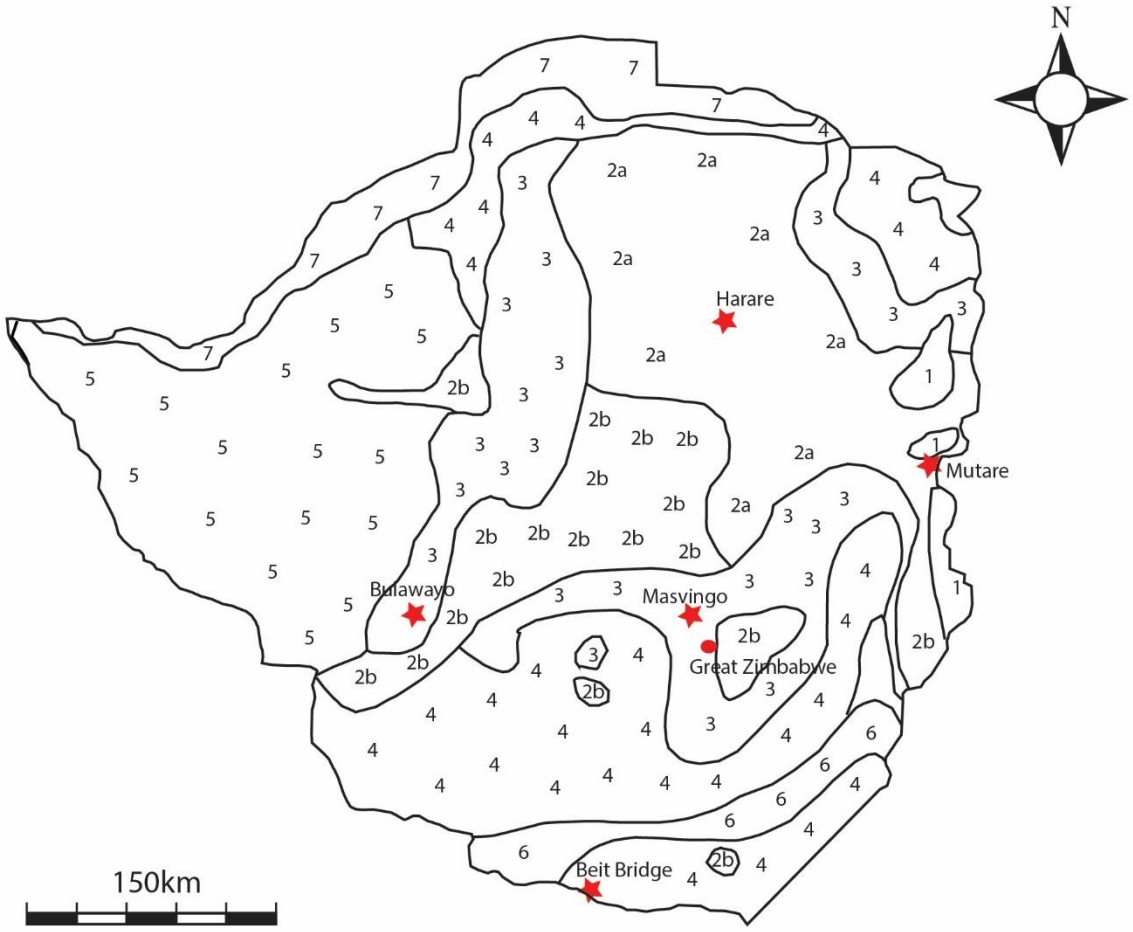
Figure 2.3: Distribution of vegetation types in Zimbabwe Source: (http://www.lib.utexas.edu/maps/africa). Note that Fort Victoria is now called Masvingo, and Salisbury is now Harare.

Vegetation characteristics are important for livestock pasturing, as domesticates feeding on sourveld grasses lose body weight during the dry winter due to the low forage quality, which may be too low for efficient digestion. Sweetveld forage quality does not decline on a seasonal basis (Ellery et al., 1995), but has a much lower carrying capacity of around 12 to 20 hectares per livestock unit, whilst the sourveld has a carrying capacity of two to three hectares per livestock unit (Gambiza and Nyama, 2000). Section 4.3.1.1 discusses stable carbon isotopes in sweetveld and sourveld in relation to their C_4 sub-types. In order to use both vegetation types for grazing, an element of herd management needs to come into play to avoid overgrazing of the nutritious sweetveld. Table 2.2 outlines the various types of grassveld

found in Zimbabwe, their ecological correlates and grazing capacities. Figure 2.4 shows where in Zimbabwe the sweetveld and sourveld grasslands are found.

Table 2.2: Grassveld types found in Zimbabwe (reproduced from (Gambiza and Nyama, 2000)**)**

Name	**Altitude (m)**	**Rainfall (mm)**	**Grazing Capacity (1 Livestock Unit= 500kgs)**	**Notes**
Mountain Grassveld	>1600	>1000	1LU: 2-3 ha	Short perennial sourveld. Located on the eastern border.
Hyparrhenia tall Grassveld	1200-1675	750-1125	1LU: 2.5-3.5 ha	Sourveld. Relatively resistant to overgrazing. Occurs from woodland to open perennial grasslands on the watersheds.
Hyparrhenia ot. Sp. Grassveld	>1200	<750	1LU: 4-5ha	Sourveld of tall perennial grasses from tree savanna to open savanna. Occurs on watersheds.
Heteropogon ot. Sp. Grassveld	N/A	N/A	1 LU: 5-6 ha	Mixedveld with medium height perennial grasses with high annuals in tree bush savanna. Sensitive to over grazing.
Eragrostis ot. Sp. Grassveld	450-1050	375-500	1LU: 7.5-10 ha	Sweet-to-mixed veld. Medium height perennial grasses with high annuals in tree bush savanna. Annuals increase in drought years. Sensitive to overgrazing.
Aristida ot. Sp. Grassveld	900-1200	500-750	1LU: 10-16 ha	Sour-to-mixed veld of short and tall perennial grasses and annual grasses in woodland and Karoo sandstone in west of country. Extremely sensitive to overgrazing.
Cenchrus ot. Sp. Grassveld	450-1000	325-400	1 LU: 7.5-10 ha	Sweetveld in a tree bush savanna with medium height perennial grasses and high proportion of annual grasses. Occurs on heavy clay basaltic soils. Sensitive to overgrazing.
Aristida-Dactyloctenium Grassveld	<600	300-600	1LU: 12-20 ha	Sweetveld in woodland or bush scrub savanna with sparse short annual grasses. Occurs on Zambezi and Limpopo River valleys. Extremely sensitive to overgrazing.



Key

1	Mountain Grassveld (Short perennial grasses)
2a	Hyparrhenia veld (Tall perennial grasses)
2b	Hyparrhenia- other species (Tall perennial grasses)
3	Heteropogon- other species (Medium to tall grass, predominantly perennial but annuals present)
4	Eragrostis (Medium height grass, predominantly perennial but with high proportion of annuals)
5	Aristida (Medium to tall grass, predominantly perennial but with high proportion of annuals)
6	Cenchrus (Medium heigh grass, perennial with high proportion of annuals)
7	Aristida- Dactyloctenium grassveld (Predominantly short annual grasses)

Figure 2.4: Distribution of grass vegetation types in Zimbabwe (Gambiza and Nyama, 2000)

Sweetveld vegetation is dominated by short shrubs with sparse tufted grassveld growing below. Common sweetveld C_4 grasses include: *Anthephora pubescens, Brachiaria nigropedata, Bothriochloa insculpta, Eragrostis superba, Schmidtia pappophoroides, Heteropogon contortus, Stipagrostis uniplumis, Chloris roxburghiana*, *Tricholaena monachne, Cenchrus ciliaris, Themeda triandra, Panicum maximum* (patches), *Digitaria eriantha* (patches) and *Neorautanenia* (Acocks, 1988). These grasses are generally found in the semi-arid lowveld regions of Zimbabwe but also in small amounts amongst sourveld grasses in close proximity to Great Zimbabwe.

C_4 sourveld grass species found around Great Zimbabwe include *Digitaria pentzii, Heteropogon contortus, Pogonarthria squarosa, Hyparrhenia filipendula, Aristida barbicollis, Setaria pallidifusca, Melinis repens* (Watson, 1992; Gusha et al., 2017). The area has a high carrying capacity of 1 LU : 4-6ha and also contains some annual sweetveld grasses amongst the sourveld species. In this area, *Themeda triandra* occurs alongside *Hyparrhenia* species on clayey loams.

Gusha et al., (2017) noticed a difference in grass species between the modern communal rangeland grazing areas and the commercial rangeland areas. Unpalatable grasses such as *Pogonarthria squarosa* were more common in the former, perhaps as a result of overgrazing. It should be noted that factors such as human activity, overgrazing and changes in land-use may lead to the vegetation at the site today being different from that during the occupation of Great Zimbabwe.

Sourveld and sweetveld vegetation have both adapted to herbivory in their own ways. For example, broad-leafed plants (more often found in sourveld areas) are typically unpalatable as they contain high concentrations of tannins whilst fine-leafed vegetation (abundant in sweetveld areas) contains long thorns to protect its palatable and nutritious leaves from being consumed by herbivores. One exception to this is the broad-leafed C_3 species *Boscia albitrunca* (shepherd's tree) which is palatable to herbivores and is heavily browsed. Another exception is C_3 *Colophospermum mopane* which is palatable to herbivores and is also heavily browsed during winter months. The primary preference for vegetation by herbivores is determined by the quality of the vegetation rather than the quantity i.e. the tannin content, the nitrogen content and their seasonal dynamics (Cowling et al., 2004). Vegetation on the landscape can be selected for during different seasons to meet the animal's nutritional requirements.

In contemporary savannas, environmental stress due to population agglomeration means that animals' flexibility in selection of resources has been reduced and their movement is constrained (Palmer and Birch, 1992). Plant diversity at Great Zimbabwe has been particularly affected by the management policies of the monument custodians (Ndoro, 2001). Population agglomeration in the communal savanna areas is rooted in the 1890s when white settlers managed land ownership through a system of state enforced repression, segregation and violence (Palmer and Birch, 1992). Black communities were forcibly removed from their land and relocated to areas with poor, infertile soils located in inhospitable and tsetse-ridden areas of the country. The residues of this regime remain, and seasonal movements of cattle herds are likely to be more limited today than in pre-colonial times.

2.3 The subsistence economy of early farming communities in southern Africa

Iron Age agro-pastoralists supported themselves by mixed farming in the form of agriculture and livestock herding, together with metal working (Maggs, 1980a; Hall, 1990). This section describes the subsistence economies of these communities.

2.3.1 Iron Age farming practices and trade commodities

Approximately 2000 years ago, an agricultural innovation occurred in the summer rainfall areas of southern Africa. Sedentary Iron Age groups arrived on the landscape, bringing with them not only livestock, but also the first agriculture and knowledge of metal working (Mitchell, 2001). Metal production in sub-Saharan Africa was a key technical development in pre-colonial Africa. It influenced almost all spheres of activity, ranging across agriculture, hunting, trade and weapons (Childs, 1991; Collett, 1993; Schmidt, 1997). The first metals worked in southern Africa were iron and copper (Childs and Herbert, 2005). Although wood and stone agricultural implements were used, iron tools allowed hard soils to be hand-tilled and crops to be harvested more easily. Evidence for iron working in southern Africa exists in the abundance of production debris such as slag, tuyeres and furnaces as well as evidence of the manufactured products for example hoes, spears and bracelets.

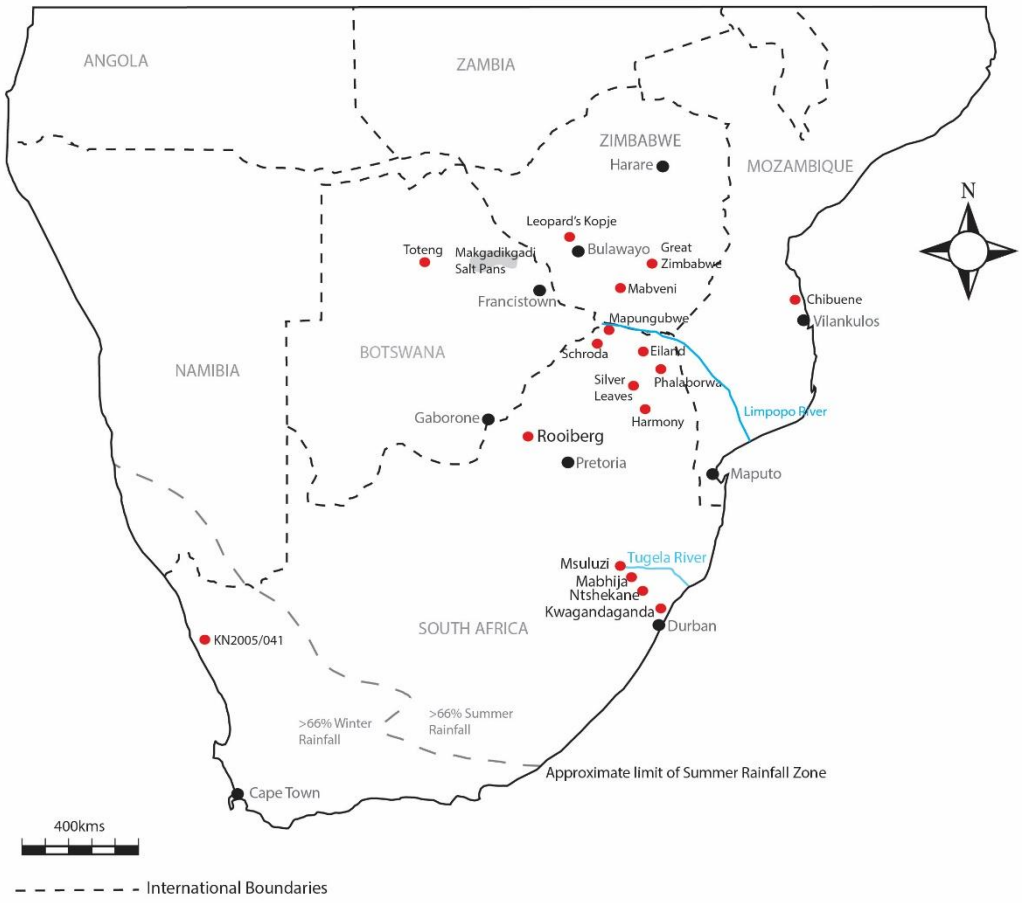


Figure 2.5: Map of southern Africa and locations of Iron Age sites mentioned in text (drawn by M. House, compiled from Maggs and Whitelaw, 1991; Robbins et al., 2005; Orton et al., 2013; Chirikure et al., 2017)

Phalaborwa (Figure 2.5), located in the Limpopo province of South Africa, is a farming site showing evidence of mining from the end of the first millennium AD (van der Merwe and Scully, 1971; Moffett, 2017). The attraction for metal-working societies in this region lies in the abundance of copper and iron ores in its vicinity. The abundant copper ore evident here still sustains the mine today. Mining was achieved in open-slopes, tunnel and underground chambers (Moffett, 2017). Deep shafts were cut into open rocks and copper ore removed by cracking the volcanic rock with fire (Hall, 1990). Iron ore was abundant in the pebbles available on the slopes of the hill. The environmentally marginal location of the site in the form of characteristic low rainfall, sporadic outbreaks of animal disease and high temperatures provided an opportunity for metal products to be bartered for items like livestock and grain (Hall, 1990). A second example of an iron-producing

site is that of Mabhija in KwaZulu-Natal of South Africa (Figure 2.5). Here too, iron-ore quarrying occurred on an extensive scale and objects such as slag, furnaces and iron implements were recovered in abundance. The environment here too, was not conducive to large-scale crop cultivation or livestock herding and it is likely that the iron implements were traded for crop and livestock products (Maggs, 1982). At Great Zimbabwe, iron slags and tuyere fragments were excavated in middens across the site (Caton-Thompson, 1931). Iron furnace remains were recovered in the western enclosure of the hill (Hall, 1905). The absence of any large area of iron production at Great Zimbabwe allows for the possibility that production centres existed on the outskirts of the site and the manufactured implements brought in for use (Swan, 2005; Mtetwa, 2017). A tin ingot excavated at Great Zimbabwe had a lead isotope ratio indicating that the raw material came from Rooiberg (Figure 2.5)- the only known location for Iron Age tin production in southern Africa (Miller and Hall, 2008). At least from the 15th century AD, tin was mined in large quantities from Rooiberg and likely exported via Great Zimbabwe and the Indian Ocean (Miller, 2002). Bronze objects made from Rooiberg tin have been recovered at various sites in northern South Africa and Botswana (Molofsky et al., 2014), with the first appearing at Mapungubwe in the form of a curved bar and wound bangle fragments (Miller, 2002).

The earliest direct evidence of crop agriculture in southern Africa is difficult to identify due to a lack of flotation conducted on excavated soils and poor preservation of the seeds in the archaeological record. Indeed, large, semi-permanent villages, grindstones (associated with grinding harvested grain) and grain stores are all indirect indicators of crop agriculture in the Iron Age (Maggs, 1980a). The earliest indirect evidence lies in north-eastern Transvaal, where seed impressions of bulrush millet (*Pennisetum glaucum*) have been found on pottery sherds dating to the third century AD at Silver Leaves (Klapwijk, 1974). Crops such as finger millet (*Eleusine coracana), Sorghum* and bullrush millet (*Pennisetum glaucum*) have been found in contexts dating to the sixth and eighth centuries AD in the Thukela Basin (Maggs, 1984; Maggs and Whitelaw, 1991). Further north, there is evidence of cultivation of cowpeas (*Vigna unguiculata)* during the seventh century AD in Limpopo (Huffman, 1972b), and of sorghum, cow peas and ground beans (*Voandzeia subterranea*) during the ninth to tenth century AD at Leopard's Kopje in Zimbabwe (Huffman, 1974) (Figure 2.5).

Cattle and goats are found in abundance at most Iron Age sites in southern Africa and this attests to their importance in the past. The earliest evidence for cattle in these areas is a fragment of cattle bone from Toteng, Botswana, which has been dated to 2070 ± 40 BP (Beta-1904888) (Robbins et al., 2005), although the identification as cattle has been questioned. A cattle horn core from Namaqualand has been dated to 1625 ± 25 BP (OxA-22933) and provides the earliest evidence to date of a directly dated *Bos taurus* (Orton et al., 2013). In the context of communities practising mixed farming in Zimbabwe, Mabveni holds the oldest associated radiocarbon date for evidence of cattle (Huffman, 1975) dating to between the 2nd and 6th century AD. Apart from their social importance (discussed in Chapter 3) domestic animals provided hides for clothing, shields, bone for artefacts, and food in the form of blood, milk and meat. Evidence for the importance of livestock also lies in the recovery of cattle figurines from various sites across southern Africa, including Leopard's Kopje (Robinson, 1966) and Schroda (Hanisch, 2002) as well as at Ntshekane (Maggs, 1976) and in the Msuluzi Confluence (Maggs, 1980b), both in KwaZulu-Natal (Figure 2.5). Possession of large herds allowed the herders to build up a network of alliances by trading and exchanging domestic stock and access to grazing land. This may have bonded settlements together, leading to the formation of political alliances and ultimately chiefdom level societies (Hall, 1990). Ecological dimensions such as the availability of good grasses can determine where a farming community settles. An example of this is the Thukela Basin in KwaZulu-Natal of South Africa. Here, Early Iron Age groups chose to settle exclusively in valleys and valley bottoms near rivers. Although water, firewood and soil would have been contributing factors to their selection of area to settle, good grazing would have been important too.

Some Iron Age sites exist near saline springs, for example Harmony on the banks of the Makhutswi River (Evers, 1979) and Eiland (Evers, 1981) in Mpumalanga Province. Both sites also yielded stone bowls indicating that these people were likely manufacturing salt either for local consumption and/or for trade. Salt crust mixed with sand is filtered through grass to produce a brine. The brine is then boiled down to form a hard crust which is easy to transport (Hall, 1990). These sites are in ecological conditions which are unfavourable to crop cultivation and it is therefore likely that salt was bartered for items like grain and livestock. Evidence for salt-workings also lie in the Makgadikgadi Pans in Botswana and it has been suggested that these sites controlled the salt trade to Zimbabwe Culture sites (Denbow, 1986).

Trade in exotics formed an important part of southern African farming economies from the mid-first millennium AD. Evidence for trading ports during the eighth and ninth centuries AD lies in the prehistoric Islamic state of Kilwa on the southern coastline of Tanzania and Chibuene on the Mozambique coastline. It is unlikely that these sites were occupied by Arab merchants continuously, but rather that people known as 'Zanj' (pastoralists who were the middlemen in transactions between the African interior and Arab traders) occupied these areas (Hall, 1990). Items like glass beads, cowrie shells, cloth and later porcelain were traded by travellers in exchange for animal skins, copper, iron, ivory and later, gold (Huffman, 1972a). Evidence of inland exotic imports exist in small amounts as early as the seventh century AD at the Early Iron Age site of KwaGandaganda in KwaZulu-Natal and later into the eighth and ninth centuries at Ntshekane. In the Limpopo Valley, earliest evidence for exotic trade lies at Schroda. Ivory working residues are abundant at these sites, but evidence for gold mining in southern Africa only appears at around the 12th century AD. Excavations at Mapungubwe yielded many gold objects from the hilltop. There is no evidence of gold working before this period, but it seems likely that techniques had advanced by this time (Phimister, 1976; Miller et al., 2000). Gold was procured either through alluvial panning or mining the gold-rich deposits which protrude through the granites (Hall, 1990). Even though cloth is not preserved in the archaeological record, we know it was manufactured and probably traded. Evidence for this lies in the substantial number of spindle whorls recovered in excavations, the earliest from Mapungubwe (Hall, 1990). The ethnographic records which detail cotton spinning only give mention to indigenous or wild cotton (Antonites, 2019). As elsewhere in the world, the process was tediously labour-intensive as the seeds had to be removed by hand after which the fibres were teased out by plucking them on a string bow.

A brief review of Iron Age subsistence economies shows that these groups were sedentary. They produced their own crops, livestock, mined metals like iron, copper and gold, manufactured cloth and salt, procured ivory and manufactured their own ceramics. It is likely that these goods were traded locally, and some items traded across the Indian Ocean for exotic imports such as textiles, glass beads, porcelain and other Asian goods. These sites, therefore, did not exist in isolation, but developed a level of inter-dependence through trading networks. The next section reviews sites in southern Africa

contemporaneous with Great Zimbabwe. These likely interacted with each other on a heterarchical, politically and economically shifting landscape.

2.3.2 The distribution of *Madzimbahwe*

Madzimbahwe (singular, *dzimbahwe*) is the Shona term for the residence of the chief (Hannan, 1974; Hall, 1990). Extensive surveys over years of research have identified more than 150 *madzimbahwe* in Zimbabwe, eastern Botswana and Mozambique (Figure 2.7) (Caton-Thompson 1931; Robinson 1961; Garlake 1970; Garlake 1973; Sinclair 1987). This excludes the numerous sites which have been destroyed by development and vandalism over the years. It has been suggested that due to the hierarchical nature of the Zimbabwe state, these smaller walled sites are likely regional centres (second-level hierarchy) falling under the Great Zimbabwe capital (Garlake, 1978). Most of these sites are distributed along the edge of the Zimbabwe plateau and have been proposed to contain their own economic hinterland whilst still being subordinate to the king at Great Zimbabwe (Chirikure, 2019).

Stone walling is by far the most prominent (and best preserved) feature of these sites, and therefore, a large amount of research has been aimed at developing a classification system which can be applied across the region (Whitty, 1961; Chipunza, 1994). The walling types all occur at Great Zimbabwe and their styles changed with time and function. The existence of these walls at the site allow for a chronological investigation into which areas were built through time. As these wall-types exist on the wider landscape, it is possible to form a chronology of occupation of the smaller walled sites and compare them to Great Zimbabwe itself.

Unfortunately, only a handful [13 sites according to the Archaeological Survey database, (Sinclair, 1987)] have been excavated which provides little understanding of how these sites interacted with one another on the landscape throughout their occupation. Some of the sites which have been investigated are Manyikeni (Garlake, 1976; Barker, 1978; Sinclair, 1987) in Mozambique and Toranju (Denbow and Wilmsen, 1986) more than 300 km west of Great Zimbabwe in the Makgadikgadi Pans in eastern Botswana. A third level of hierarchy consists of the peasant communities falling under the control of regional centres and Great Zimbabwe itself. These sites do not contain any stone walling but

contain evidence of agriculture and intensive pastoralism (for example Montevideo Ranch and Chivowa Hill). This section reviews the walling styles identified at Great Zimbabwe and other *madzimbahwe* and then explores the archaeology of smaller walled and non-walled sites contemporary with Great Zimbabwe itself.

The most important feature is the 'coursing' of the walls. Figure 2.6 illustrates the types of coursing one might find at Zimbabwe Culture sites. P coursing is the earliest type (Whitty, 1961; Chipunza, 1994). It is poorly coursed, using granite blocks which have not been shaped into regular sizes. Q is the most neatly coursed walling associated with the most refined walling at Great Zimbabwe. In this case, the stonemason has dressed the blocks into similar sizes creating a neat, homogenous wall. Some walls have a combination of P and Q courses which is an intermediate style showing development of the former wall style to the latter. R walling is the latest and its interpretation is ambiguous. Either it occurs from the addition to an existing wall, or in areas which are less important such as cattle pens and boundary walls (Pikirayi, 2001).

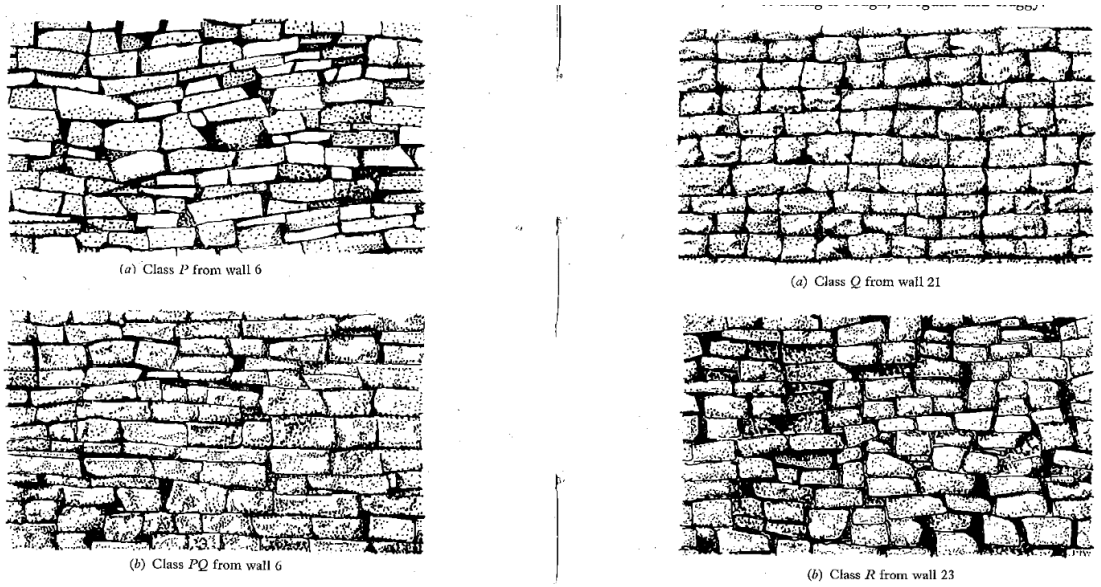


Figure 2.6: Illustration of P, PQ, Q and R-style walling (after Whitty (Whitty, 1961)**)**

The classification system broadly divides the freestanding walls into three categories. Style I with P coursing and square entrances occurs exclusively at Great Zimbabwe itself. Style II with Q coursing and rounded entrances occurs further afield across the Zimbabwe plateau. Style III has rounded entrances and revetment walls with square passages built with Q coursing and a check design which occurs at Khami (Sinclair, 1987).

Attempting to identify the origin of Zimbabwe Culture freestanding walling styles is extremely difficult. This is partly due to the scarcity of radiocarbon dates at the few well-studied sites and partly due to the lack of research at other Zimbabwe-type sites besides Great Zimbabwe itself. This is further complicated by the subjective method of separating northern Leopard's Kopje walled sites (which pre-date Great Zimbabwe) from Zimbabwe Tradition walling. One hypothesis proposes that terraced uncoursed walling (found at Leopard's Kopje sites such as Mapungubwe and Mapela Hill) shows an experimentation with stonemasonry. As technical masonry skills developed, granite boulders were cut into regular blocks making it possible to build free-standing walls as those found at Great Zimbabwe. Another similar hypothesis suggests that terraced walling developed into freestanding walls in eastern Botswana in the Mupani cluster (see Figure 2.6 for location) which were later expressed at Great Zimbabwe (Van Waarden, 2011). This hypothesis is supported by evidence for a progression of walling style from P to Q in Mupani cluster sites assumed to pre-date Great Zimbabwe. An alternate hypothesis suggests that Zimbabwe Tradition sites express a completely different ideology to Leopard's Kopje states, allowing for the possibility of a Great Zimbabwe origin for Zimbabwe Tradition walling (Garlake, 1970; Chirikure et al., 2018b).

Regardless of where Zimbabwe-type walling originated, by around AD1400, freestanding walls are a prominent feature across the Zimbabwe plateau and further to the east and west. Walled sites can be found as far west as the Sowa Pans in Mozambique and as far east as the Mozambique coastline (Hall, 1990; Pikirayi, 2001; Van Waarden, 2011). The fact that sites such as Manyikeni and Toranju lie so far from Great Zimbabwe (see Figure 2.7 for locations) has caused debate about their economic and political affinities with Great Zimbabwe (Garlake, 1978; Hall, 1990; Van Waarden, 1998; Pikirayi, 2001; Van Waarden, 2011). It is unlikely that these sites existed on the landscape in isolation and some researchers have suggested that they might indicate the movement of groups of stonemasons, or political expansion from the centre at Great Zimbabwe (Garlake, 1970). There are probably more, as yet undiscovered regional centres in intermediate areas or the outlying centres may have had a specialised political and economic relationship with the central state at Great Zimbabwe (Hall, 1990).

Other researchers think the smaller walled sites may not have fallen directly under the king at Great Zimbabwe, but rather represented chiefdom level sites on the edge of the hegemony (Pikirayi, 2001). The distance between the smaller sites and Great Zimbabwe

make it unlikely that the Great Zimbabwe kings could successfully control such a large area (Pikirayi, 2001). Pikirayi (2001) proposed that these chiefdoms may have believed they were not benefiting sufficiently from the Zimbabwe state and turned their allegiances to individuals closer to home. Further, stone walled sites in eastern Botswana pre-date Great Zimbabwe (Van Waarden, 1998, 2011). It is likely that these walled sites were an expression of power and influence within the Leopard's Kopje Culture and may not have been related to the Zimbabwe Culture at all (Chirikure et al., 2016b).

There are many smaller sites contemporary with Great Zimbabwe that are much closer to it (see Figure 2.7). Few have been excavated, but there have been attempts to identify the economic relationship between these sites and Great Zimbabwe (Sinclair, 1987). The smaller sites were probably rural regional centres falling under the rule of the Great Zimbabwe hub and forming the second tier of hierarchy within the Zimbabwe state. These sites were usually built on hilltops and contain walling stretching between natural features to form an enclosure (Huffman, 2009a). Sites such as Nenga, PaMuuya and Harleigh Farm contain hilltop enclosures only large enough to contain one or two families. Copper, glass beads and ivory in the hilltop enclosures at Tsindi and Harleigh Farm have been interpreted as evidence of high status (Rudd, 1968, 1984). At Chumnungwa, seven burials within the stone enclosures contained gold objects which have been interpreted as status indicators (Garlake, 1973). Ruanga, too, contained stone enclosures on the hilltop and associated high status goods such as gold, copper and glass beads, but at the foot of the hill, wood and plaster houses contained only practical household utensils (Garlake, 1973). Sites such as Lekkerwater and Ruanga show evidence of intensive animal husbandry (Sinclair, 1984). These sites are located in drier areas (see rainfall map in section 2.2.1) so agriculture was probably less important compared with sites such as Castle Kopje (Tagart and Brinn, 1997). Instead, it has been proposed that these sites built up herds of cattle and sent them to Great Zimbabwe, probably both as an economic source for trade and as tribute to their king (Sinclair, 1987).

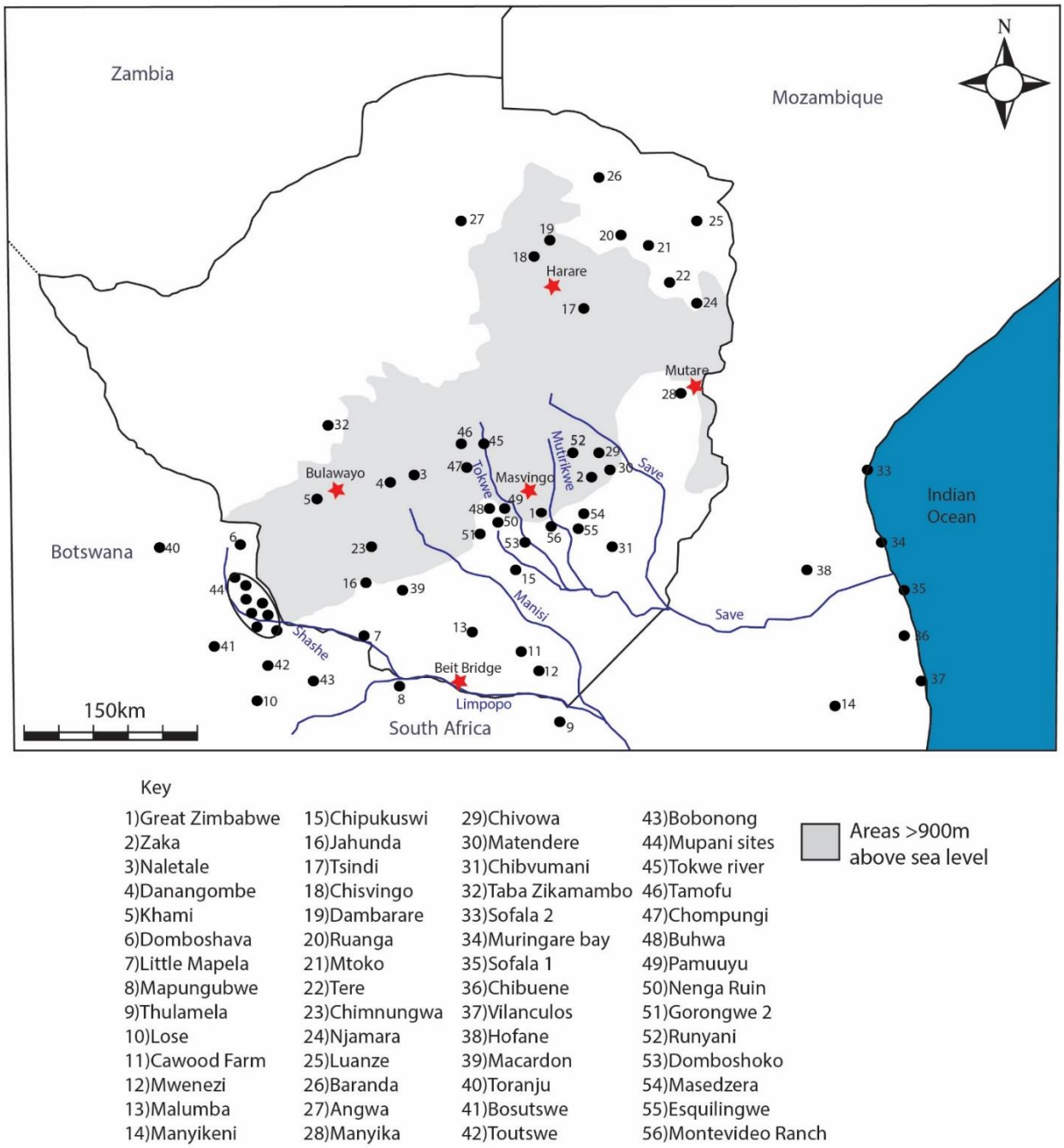


Figure 2.7: Distribution of sites occupied during the Zimbabwe Period. Grey area of the map illustrates the extent of the Zimbabwe plateau (drawn by M House).

The third tier of hierarchy within the Zimbabwe state consisted of sites which were subordinate to the regional capital and the centre itself. These sites are unwalled and as such have been little studied by archaeologists. One example is Montevideo Ranch, approximately 40 km south of Great Zimbabwe. The site is in close proximity to copper mines and there are remains of iron smelting (Sinclair, 1987). There is evidence of

agriculture in the form of hoes. There is also good winter grass. It has been suggested that cattle moved seasonally between Great Zimbabwe and Montevideo Ranch in order to maximise nutrient intake of the herds (Sinclair, 1987). Similarly, Chivowa Hill is located 60km north-east of Great Zimbabwe and contains a possible grain bin, a house floor, clay figurines of animal and human form, and soapstone, shell and bone ornaments (Sinclair, 1987; Hall, 1990). It is likely that hundreds of similar sites are dotted across the landscape, forming the base for the majority of the population within the Zimbabwe State (Hall, 1990). Future work targeting these sites could illuminate this little-understood portion of the Zimbabwe state.

2.4 A description of the main occupation areas at Great Zimbabwe

Great Zimbabwe is one of the most famous Iron Age sites in Africa. It extends over 720 ha and is known especially for its dry-stone walling, built from granite quarried in the nearby hills. Some walls reach a thickness of four metres and are built with a degree of precision that would have demanded a highly skilled workforce. Stone walling is ubiquitous at the site and emphasises its grandeur and prestige. The three main occupation areas at Great Zimbabwe are the Hill Complex in the north, the Great Enclosure in the south and the Valley Enclosures in the south-east. Estimates of peak population size range from 10 000 people (Chirikure et al., 2017) to between 11 000 and 18 000 people (Pikirayi, 2001; Huffman, 2007a).

Lesser studied areas include some small walled ruins (for example the South East Ruins and the Maund Ruins) and unwalled areas sandwiched between the walled areas (See Figure 2.8) (Ndoro, 2001; Chirikure et al., 2018b). Much archaeological material has unfortunately been lost because of amateur archaeologists looting the site in search of valuables. Nonetheless, beginning in the early 20th century, numerous professional archaeologists made an effort to treat the deposit with integrity and developed hypotheses of the settlement history, use of space and chronology of the site. Figure 2.9 shows the areas excavated by professional archaeologists (Randall-MacIver, 1906; Caton-Thompson, 1931; Robinson, 1961; Summers et al., 1961; Summers, 1965; Garlake, 1973; Collett et al., 1992; Chipunza, 1994; Thorp, 1995; Chirikure et al., 2016b). Contrary to

19th century understandings, we now know that Great Zimbabwe was built and occupied by Karanga speaking people[3].

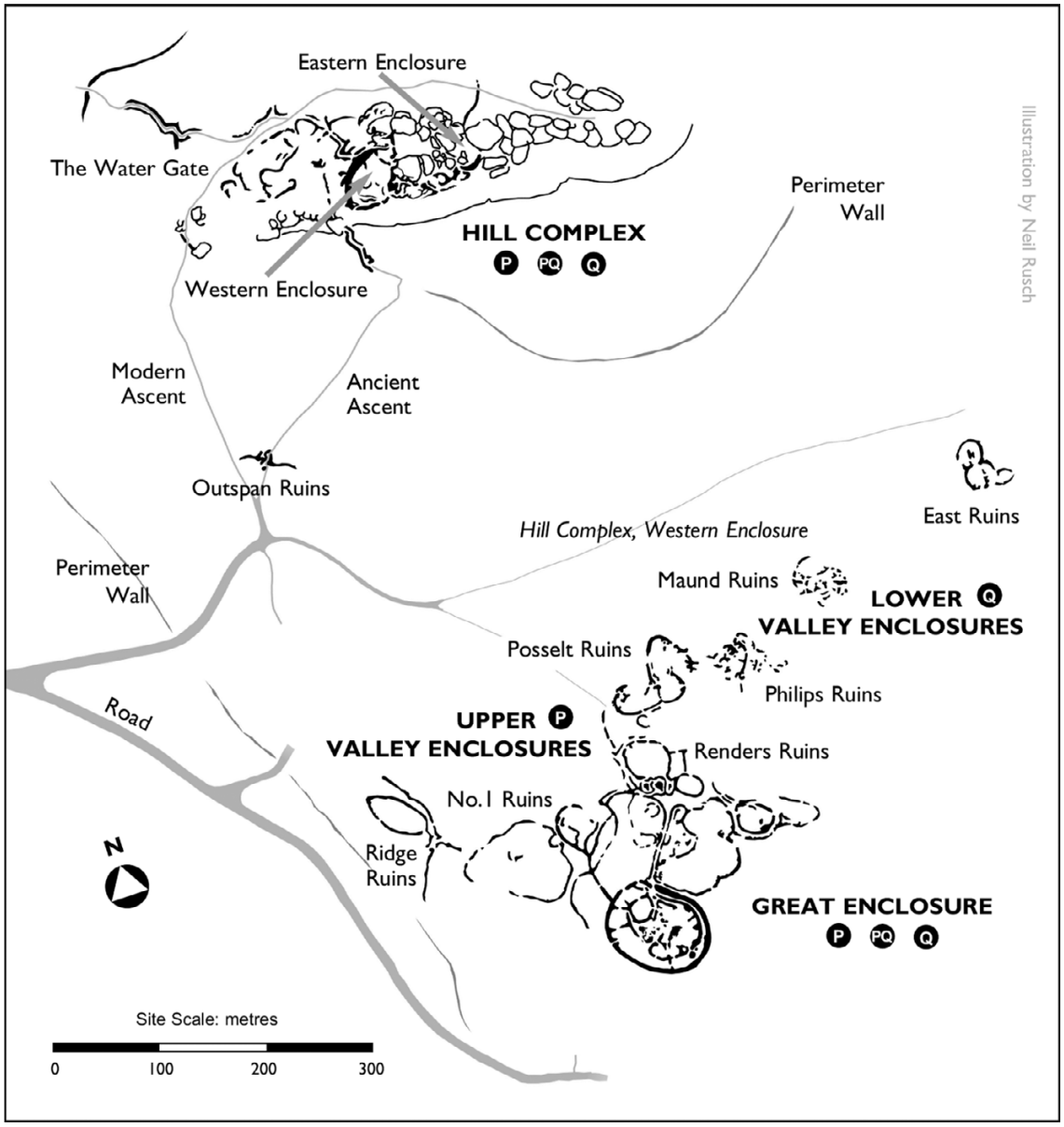


Figure 2.8: Main occupation areas at Great Zimbabwe showing types of walling in each area (Chirikure and Pikirayi, 2008)

[3] Karanga is the most common dialect of Shona which is spoken by the occupants of south-central Zimbabwe (Ndoro, 1997).

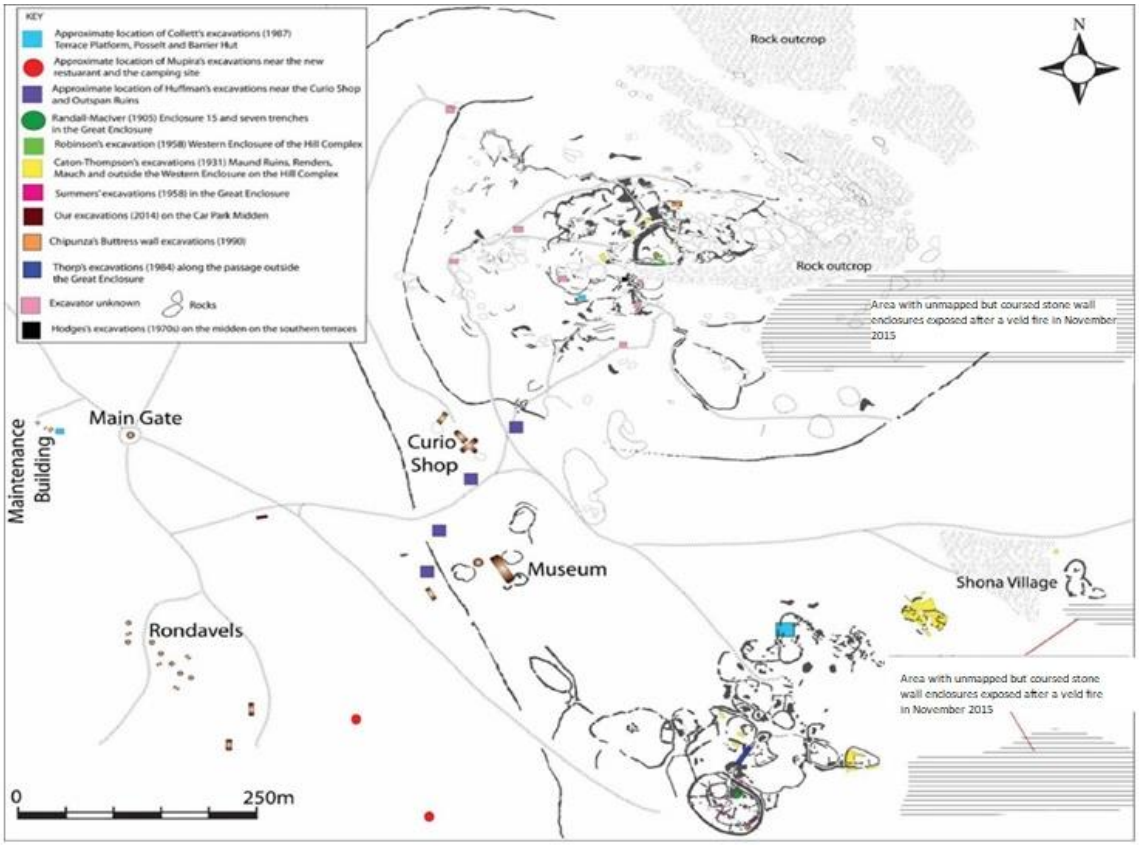


Figure 2.9: Plan of Great Zimbabwe showing excavations areas by professional archaeologists [Reproduced from Chirikure et al., (2016a)**]**

The site was occupied from the Early Iron Age (~AD300) to the historical period with the most intensive occupation from AD1200-1700 (Chirikure et al., 2018a; Chirikure, 2019). Extensive excavations allowed five periods to be identified at the site (Caton-Thompson, 1931; Robinson, 1961; Summers et al., 1961). As more research was conducted at Great Zimbabwe, the chronological sequence was refined (Huffman, 1996a, 2007a; Chirikure and Pikirayi, 2008; Pikirayi and Chirikure, 2011). The material culture associated with each of the five Periods is summarised in Table 2.3 and will be referred to throughout this section.

Table 2.3: The five periods of occupation at Great Zimbabwe and associated material culture. (Reproduced from Chirikure et al., (Chirikure et al., 2016a)**)**

Period	Material culture	Sources
1 (AD300-500) – Early Iron Age Gokomere settlement (AD600 – 900) - Early Iron Age Zhizo settlement	Pottery, pole and *dhaka* fragments, bone	Caton-Thompson (1931) Robinson (1961), Great Zimbabwe Conservation Centre Archives, Iziko Museums of Cape Town
	Pottery, pole and dhaka fragments, bones	Caton-Thompson (1931: 210), Robinson (1961)
2 (AD900-1000) - Late Iron Age Gumanye settlement	Pottery, bone points, bone, glass beads, figurines, slag, crucible, pole and dhaka fragments, possible stone walled terraces, iron, copper, bronze	Caton-Thompson (1931: 210), Robinson (1961), Great Zimbabwe Conservation Centre Archives
3. (AD1000 to 1200) - Late Iron Age settlement	Pottery, glass beads, dhaka fragments, remnant infrastructure for houses, iron, copper, bronze, brass, gold objects and slag, crucibles, stone walls, soapstone objects	Caton-Thompson (1931: 210), Robinson (1961), Summers (1971)
4 (AD1200-1700) – Late Iron Age settlement (flourishing of Great Zimbabwe)	Pottery, glass beads, celadon, porcelain, iron, copper, bronze, brass and gold objects and slag,,, crucibles, tuyeres, stone walls, soapstone objects	Robinson (1961), Summers (1971), Chirikure et al. (2013, 2016)
5 (AD1700 -1900) - Late Iron Age settlement)	Glass beads, pottery, remains of houses, bone, iron, copper, bronze, brass and slag,	Summers et al. (1961)

Period I is the earliest phase found at the site. Period I occupations are not associated with any stone walling (although it is possible that walling material from this period was re-used by later occupants), and no remains of *daga* dwellings have been recovered.

Period II is associated with Class 2 pottery wares characteristically showing flattened rims, coarse fabric and slightly hollowed bases (Robinson, 1961). Houses were built of pole and *daga*. Excavations recovered translucent snapped cylinder glass beads. No stone walling is associated with this period.

Period III shows an abrupt change in house construction (Robinson, 1961). The previous pole and daga houses had been flattened and were mostly replaced by substantial *daga* floors and walls. The construction of the south wall of the Western Enclosure began during this occupation. Although it is impossible to approximate the height of the wall during this phase, the stratigraphy shows that it is likely that the wall was built up against a mound of *daga* forming a terrace. This wall seems to be the only one on the hill on which construction began in this period. Pottery differed from the previous period in vessel shape, type of clay used, finish and decoration. The glass beads were of a different series and consisted mostly of oblates. In all, this period was described as one of "energy, organization and improved craftmanship." (Robinson, 1961, p. 187).

Period IV is associated with a sudden change in building techniques. The *daga* used to construct the houses was of inferior quality when compared to earlier periods, but the stone walling was of the highest quality found across the site. A new pottery tradition appeared (Class 4) with characteristically low-fired fabrics creating a 'sandwich effect' in the profile, frequent black burnishing and thinner walls, and a sudden increase in gold, beads and other luxury objects.

Period V represents historical populations from the 18th century onward

The three most researched areas of Great Zimbabwe are the Hill Complex to the north, the Great Enclosure to the south and the Valley Enclosures to the south-east. Dry stone walling built from granite quarried in the nearby hills is ubiquitous at the site and emphasises its grandeur and prestige. Some walls reach a thickness of four metres and are built with a degree of precision that would have demanded a highly skilled workforce.

2.4.1 The Hill Complex

In the northern-most section of the site lies a narrow ridge of bare granite some 300ft high. On top of this ridge, various small stone-walled enclosures separated by narrow passages are bounded by a sheer-faced cliff (Figure 2.10). Known as 'the Acropolis' in early literature (Caton-Thompson, 1931), this occupation area is now widely known as the 'Hill Complex'.

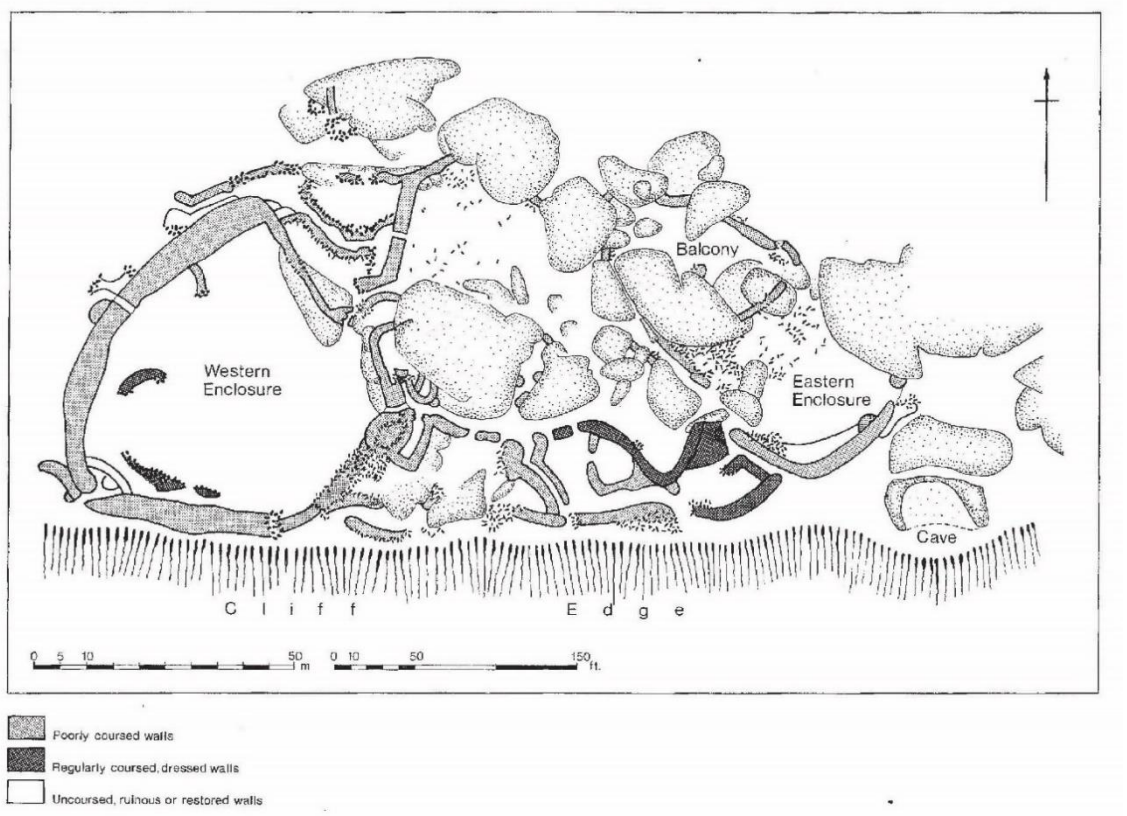


Figure 2.10: Plan of the Hill Complex (reproduced from Garlake (1973)**)**

Caton-Thompson (1931) and Robinson (1961) excavated the Hill Complex most extensively (see Figure 2.9 for locations of trenches) and to date theirs are the only published reports of excavations on the hill. The Hill Complex shows the longest sequence of occupation at the site dating from the Early Iron Age through to the Historical period.

The Western Enclosure is bordered by two curved walls over 30ft high topped with monoliths. Inside the enclosure, Robinson (1961) excavated a deposit up to 14ft deep resulting from *daga* structures being built, demolished and rebuilt (Garlake, 1973). Material culture recovered here includes ivory beads, glass beads, porcelain and metal objects.

The Eastern Enclosure is found in the eastern-most section of the hill. It too is bounded by a regularly coursed wall to the south. Garlake (1973) reports that this wall contains small triangular-shaped decoration resulting from the strategic placement of the stone blocks. Six of the famous soapstone birds were recovered here (Figure 2.11).

Up through a narrow passageway created by granite boulders lies the most elevated enclosure on the hill, referred to as 'the Balcony' (Garlake, 1973). One of the soapstone

birds was recovered from this area by Hall (1905) (Figure 2.11 shows photographs of six of the soapstone birds recovered from the Hill Complex). Other soapstone objects were also recovered from various excavations (Figure 2.12)

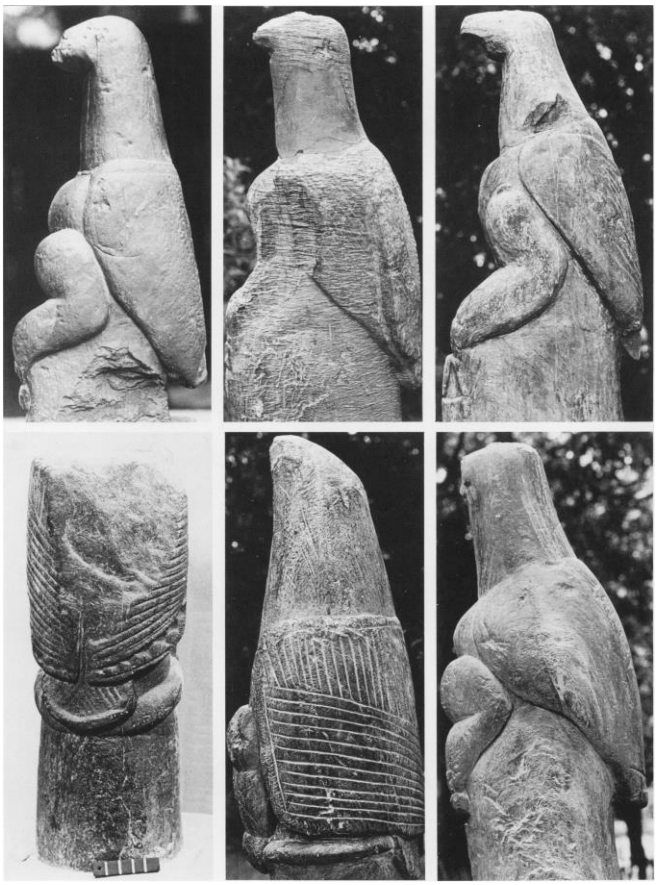


Figure 2.11: Six of the soapstone birds recovered from the Hill Complex (reproduced from Huffman (1985))

Figure 2.12: Soapstone bowl fragment containing animal motifs recovered from the Hill Complex (reproduced from Chirikure and Pikirayi (2008)**).**

A few feet beneath the Eastern Enclosure is a cave which contained metal-making residue. Because of the way noises inside the cave echo, this is believed to have once been a communication vehicle to the valley below.

2.4.2 The Great Enclosure

The Great Enclosure is located on the opposite side of the valley to the Hill Complex, on a granite shelf. The outer wall is over 800ft long, a maximum of 17ft thick and 32ft high, forming an irregular ellipse (See Figure 2.13 for plan).

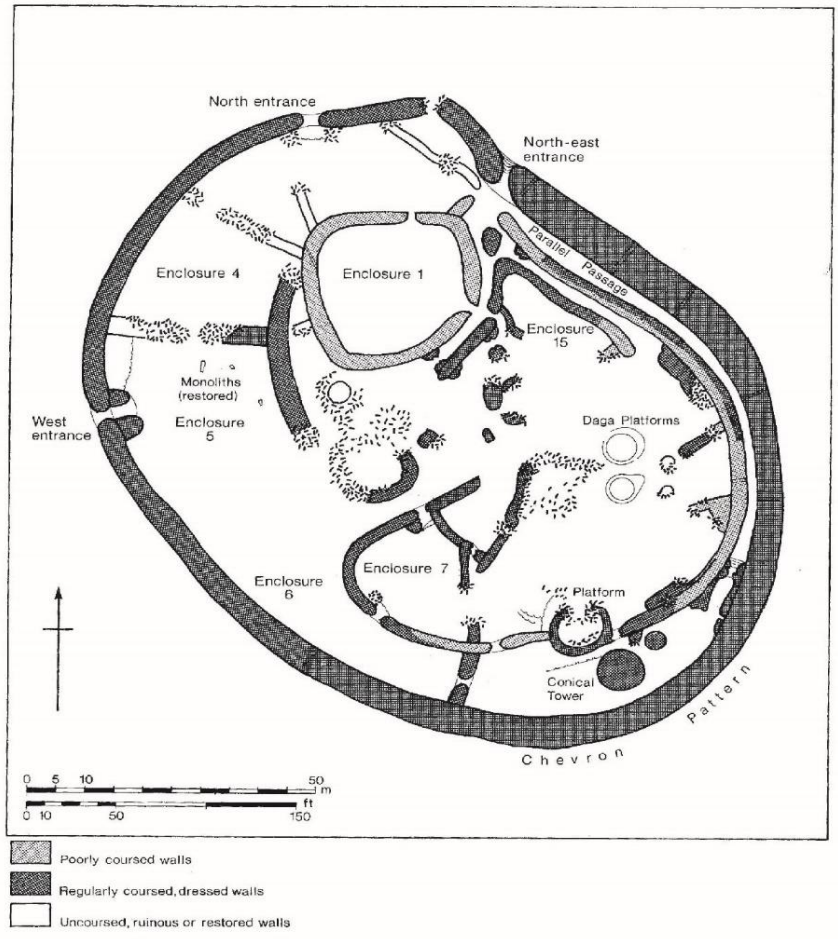


Figure 2.13: Plan of Great Enclosure (reproduced from Garlake, 1973)

The Enclosure itself contains approximately 182 000 cubic feet of stone work, more than the rest of Great Zimbabwe combined (Garlake, 1973). Inside, there is one complete enclosure (labelled 'Enclosure 1' in Figure 2.13), and several curving walls, probably used to enclose *daga* dwellings. Whitty (Whitty, 1961) and later Garlake (1973) proposed

that the inside walls pre-date the outer wall and are contemporary with the first wall on the Hill Complex as well as the earliest buildings in the Valley Enclosures. The outside wall is capped by monoliths and is more regularly coursed. It runs parallel to the earlier inside wall creating a 'parallel passage'. The eastern section contains two lines of chevron decoration towards the top of the wall (Figure 2.14). The south-eastern section of the Great Enclosure contains a cone-shaped, well-coursed, conical tower (Figure 2.15).

Figure 2.14: Great Enclosure outer wall showing chevron decoration (taken from Chirikure and Pikirayi (2008)**).**

Figure 2.15: The Conical Tower in the Great Enclosure (taken from Chirikure and Pikirayi (2008)**)**

The earliest evidence for occupation at the Great Enclosure is Period III or III influenced by IV (Sinclair, 1987). Material culture associated with this area includes evidence for metal working (slag) (Willoughby, 1893; Hall, 1905; Caton-Thompson, 1931), soapstone objects (Willoughby, 1893), Arabian glass pottery vessels (Caton-Thompson, 1931) and Class 4 pottery (Robinson, 1961).

Caton-Thompson (1931) and Summers et al. (Summers et al., 1961) excavated various areas of the Great Enclosure. With the goal of identifying the origins of Great Zimbabwe, Caton-Thompson (1931) excavated a vertical trench beneath the conical tower. The lack of exotic material culture combined with a comparison of material culture to surrounding sites, encouraged her to conclude that the site was of Shona origin (rather than Arab, Indian or Persian). Summers et al. (1961) also excavated a series of trenches in the Great Enclosure, inside and outside the parallel passages and inside Enclosure 1.

2.4.3 The Valley Enclosures

A series of small enclosures known as the Valley Enclosures lie between the Hill Complex and the Great Enclosure (See Figure 2.15, Valley Enclosures are the walled areas to the right of the Great Enclosure in the photograph). Ridge Ruins No. 1 Ruins, Renders Ruin and Posselt Ruins are closest to the Great Enclosure, with Maund Ruin and the East Ruins seemingly forming their own unit. The architectural styles of the walling show that all but the East Ruins are contemporaneous with the Great Enclosure and the Hill Complex occupations (Garlake, 1973).

Figure 2.16: Valley Enclosures are the walled areas to the right of the Great Enclosure in the photograph. Source: https://wikivisually.com/wiki/Great_Zimbabwe

Caton-Thompson (1931) and Collett et al., (1992) excavated most extensively in these enclosures and identified various house floors associated with the stone enclosures. Material culture in this area included iron slag and blooms (Collett et al., 1992), soapstone objects (Caton-Thompson, 1931) including the lower half of the eighth Zimbabwe soapstone bird (Matenga, 1998), the largest number of imported glass beads, gold wire, iron spoons, a lamp stand, two finger rings and several kilograms of wire, cowrie shells and coral (Hall, 1905).

2.5 A review of interpretations of Great Zimbabwe

This section reviews how and when Great Zimbabwe became such a significant site in southern Africa, the sequence of occupation at the site, what we know about animal husbandry practices, and its eventual decline as a centre of political power and controller of trade in the region.

2.5.1 The rise of Great Zimbabwe

The earliest evidence of occupation at Great Zimbabwe is that by Gokomere and subsequently Zhizo groups in the first millennium AD. Evidence of this occupation in the form of ceramics and radiocarbon dates lies in the Western Enclosure of the Hill Complex and in an open area below the hill (Huffman, 1991). These Early Iron Age groups have been identified across a large area from the Shashe-Limpopo Basin, up to the central Highlands of Zimbabwe. It has been suggested that the archaeological remains on the hilltop at Great Zimbabwe result from use of this locality for rainmaking ceremonies (Huffman, 1991, 2009).

Some researchers believe that the origins of the main Great Zimbabwe occupation can be found in the Limpopo Valley. From around AD1000, Leopard's Kopje cultural groups occupied the Limpopo Basin and set up their capital at K2, at the foot of Bambandanyalo Hill in Limpopo, South Africa. People inhabited the site for some 200 years from around AD1000 to 1200, leaving stratified, superimposed house floors and deep midden deposits with tightly clustered radiocarbon dates attesting to a thriving centre (Hall, 1990). These groups controlled the distribution of exotic goods such as glass beads and cloth in exchange for locally produced items such as ivory, and possibly animal skins, iron and copper (Hall, 1990). Evidence for this lies in the thousands of imported glass beads recovered from the site. The K2 communities also melted down and re-worked the beads into larger cylinders termed "Garden rollers". At K2, there is a direct focus on cattle which were kraaled exclusively at the centre of the settlement next to the court where meetings would have taken place (Voigt, 1983). There is no evidence of spatial separation of social classes at K2. The leadership within the political structure has been suggested to be hereditary (Huffman, 2007b, 2009a).

By AD1220, the central court midden at K2 had grown to a thickness of nearly 6m and the site housed an estimated 1500 to 2000 people (Huffman, 2009a). It has been suggested that the regional importance of K2 resulted in crowding, leading to its abandonment and the contemporaneous occupation at Mapungubwe Hill, just a short distance away (Huffman, 1982; Hall, 1990). There is no evidence of cattle dung (in the form of kraals) at the foot of Mapungubwe Hill where the new court is presumed to have been; as such, cattle at Mapungubwe were not kept next to the court as they were at K2. The only known cattle kraal at Mapungubwe lies on a plateau a few hundred metres to the north of the site

(Meyer, 1998). Most of the population resided near the court at the foot of Mapungubwe Hill. A few individuals, hypothesised to be elite rulers, occupied the hilltop (Huffman, 2009a). Substantial structures proposed to have been the king's residence were excavated in this area (Huffman, 2009a). These include stone walling, thick *daga* floors and elite graves with grave goods including thousands of glass beads and gold objects, for example a golden 'sceptre' and a golden rhinoceros. Both the unequal distribution of goods and the movement of leaders on to the hilltop demonstrate for the first time in southern African prehistory the physical separation of a leader from ordinary people. This spatial shift represents the first evidence of class distinction (Huffman, 1982, 1996b, 2009a). Mapungubwe continued to regulate trade in the region until AD1300 when it was abruptly abandoned as a major centre (Huffman, 2009a).

There have been suggestions that the decline of Mapungubwe as a regional centre of power and its abandonment were caused by a widespread drought that affected the Limpopo Basin (Huffman, 2009a, 2009b). Evidence for this includes stable carbon isotope analyses of growth increments of baobab trees in the Pafuri and Mapungubwe areas showing an early 14th century drought at the same time as the abandonment of Mapungubwe (Woodborne et al., 2015). More regional environmental proxies including speleothems from Cold Air Cave, northern South Africa (Holmgren et al., 1999; Lee-Thorp et al., 2001), Dante Cave speleothem from Namibia (Sletten et al., 2013) and diatom records from Lake Sibaya (Stager et al., 2013) show erratic periods of high and low rainfall from AD1300 to AD1800.

Material cultural has also been used in the form of evidence of drought periods in the Shashe-Limpopo Basin. Ethnographic information shows that during drought periods, it is common practice for the ritual burning of grain bins to take place as a symbolic process for the drought to end. Huffman and Woodborne (2016) have correlated drought events in the stable carbon isotope analyses of growth increments of baobabs to burnt grain bins in the archaeological record. The Zimbabwe plateau is located some 300kms north-east of Mapungubwe. Given the high rainfall in the area around Great Zimbabwe (Figure 2.1), it is likely that even during a drought, this area would have received more rain than surrounding regions. That would have made it a sought-after focus for settlement at that time. The occupation at Great Zimbabwe becomes more intense at AD1300 and there have been suggestions that the ceramics are similar in form and decoration to those at

Mapungubwe. These lines of evidence have been used to infer a Mapungubwe origin for Great Zimbabwe (Huffman, 1982, 1996a, 2007a, 2009a)

The model outlined above has been hotly contested in light of recent research (Chirikure and Pikirayi, 2008, Chirikure et al., 2011, Chirikure et al., 2013; Chirikure et al., 2014; Chirikure et al., 2017; Chirikure et al., 2018). Bayesian modelling shows that the periods of intense occupation at Great Zimbabwe and at Mapungubwe overlapped for some 100 years which casts doubt on a Mapungubwe origin for Great Zimbabwe (Chirikure et al., 2013b). The presence of thousands of "Garden roller" glass beads and abundant deposits at Great Zimbabwe throughout the K2 and Mapungubwe periods may indicate that, even during K2 times, Great Zimbabwe was already a place of importance whilst K2 and Mapungubwe were regional centres (Robinson, 1961; Wood, 2011; Chirikure et al., 2012). Chirikure et al., (2013a) also dispute Huffman's (2009a) claimed similarities in ceramics at Great Zimbabwe and Mapungubwe. Ceramics from Great Zimbabwe contemporaneous with those at Mapungubwe are sparsely decorated, unlike the Mapungubwe ceramics which are lavishly decorated (Chirikure et al., 2013b). This school of thought holds that it is likely that Great Zimbabwe was occupied at the same time as K2 and Mapungubwe because it was its own independent polity on the landscape (Chirikure et al., 2018b).

Pikirayi (2001) and Garlake (1978) argue that the significance of local wealth in the formation of state polities has been overlooked as a result of a focus on trade in exotics. Pikirayi (2001) notes that before the rulers at Great Zimbabwe could have accumulated the labour force to build the extravagant stone walling seen from Period III, they would had to have set up a system of taxing from their subordinates. Surplus goods and labour force could also be obtained through collective action, reciprocity and cooperation (Chirikure, 2019). Further, political ideology and religious commonality would have united the residents into a community which bolstered the place as a centre before Period III occupations (Pikirayi, 2001). Garlake (1978) proposed that Great Zimbabwe rose to power due to the accumulation of wealth in cattle. This wealth could be used to obtain the labour necessary to construct the massive stone walls and therefore monopolise trade.

The rise of Great Zimbabwe to become a major economic and political centre also involved the flow of trade goods across the Indian Ocean (Wood, 2005). Textiles, porcelain, glass beads and other exotic imports were imported into Great Zimbabwe in return for gold, ivory, animal skins and possibly iron and copper. From this, researchers

have hypothesised that due to the access to the trading post at Sofala, Great Zimbabwe could monopolise exotic trade and build its wealth (Hall, 1990). The relative importance of these various factors in the rise of Great Zimbabwe have been hotly debated.

2.5.2 The use of space at Great Zimbabwe

The occupational sequences at Great Zimbabwe are extremely complex given the long history of settlement and the extent of the site, with multiple foci of activity. For decades, archaeologists have attempted to understand the use of space at the site and this has resulted in two main streams of thought.

Huffman uses a cognitive structuralist framework to interpret the layout and use of space at Great Zimbabwe (Huffman, 1982, 1984, 1996b, 2009a). He suggests that, in accordance with the principles of sacred leadership, the king had to live on high ground and in this case, resided on the hilltop in the Western Enclosure (Huffman, 2010). The presence of monoliths is seen as an indication that this is a male domain. The ritual centre was in the Eastern Enclosure of the hilltop as, according to Shona oral traditions, private ceremonies occur at the back of the settlement. The big open area beneath the hill is where the court was located. This was where meetings would have taken place amongst the men. The kings' wives would have resided in the Valley Enclosures, and initiations would have taken place in the Great Enclosure. The commoners would have resided in the flat, unwalled areas around the base of the hill. This is supported by excavations yielding utensils, domestic pottery, iron hoes and common ornaments such as glass beads and metal bangles from the flat areas. Huffman argues that this settlement layout continued until Great Zimbabwe collapsed as a state capital (Huffman 1996).

Multiple scholars have critiqued this interpretation on the grounds that it misuses ethnography, does not take into account possible changes in the use of space through time, and is biased towards stone walled areas, leading to distorted interpretations of material culture (Beach, 1998; Lane, 2005; Beach et al., 2007; Chirikure and Pikirayi, 2008; Pikirayi and Chirikure, 2011; Chirikure et al., 2013a, 2016b) Assuming that use of the whole site was governed by the same structural principles for the entire occupation does not allow for any fluidity or change (Collett et al., 1992; Beach, 1998; Chirikure et al., 2016b). Excavations in the Valley Enclosures showed intensive occupation in the form

of middens. The material culture which included a fragment of blue-on-white porcelain showed a late occupation and post-dates Huffman's hypothesised abandonment of the site at AD 1450 (Collett et al., 1992)

Chirikure et al., (2018b) argue that, on the basis of available evidence, the occupation areas at Great Zimbabwe appear to be homesteads whose occupants were practising more or less the same activities. Chiripanhura (2017) conducted an extensive analysis of material culture from archive material from various excavation areas of the site. She found that the same material cultural was scattered across the whole site. The implication is that inferring use of space based on context of material culture alone may be problematic. It is therefore incorrect to designate activity areas when the material culture is generally similar across the whole site. This view is supported by Shona ethnographies and historical records, which indicate that shifting powers in the form of rotational succession is common practise in Shona society (Beach, 1974a, 1974b, 1998). A study of the material culture at the whole site supports a form of rotational succession, rather than segregated activity areas as proposed by Huffman (Huffman, 1996b, 2007a, 2009a). Exotic imports recovered from the Great Enclosure, the Hill Complex and the Valley Enclosures supported the hypothesis of elite activities being carried out in these domains (Chirikure et al., 2018b). The main argument here is that if exotic imports are a status indicator (Huffman, 1982) and are recovered across the whole site, what does this say about the status of the people who use them?

2.5.3 Animal husbandry at Great Zimbabwe

Studies of cattle remains from Great Zimbabwe have been limited to identifying the distribution of skeletal elements, age profiles and herd composition and making comparisons with other Zimbabwe-type sites. Archaeologists have used the age profiles of the cattle as well as environmental factors to hypothesise where the cattle might have come from (Garlake, 1978; Barker, 1978). The rationale behind this is that if older animals were found in abundance, this would imply breeding herds in close proximity to the site (Garlake, 1978; Thorp, 1995). This section reviews previous studies of the faunal remains and consolidates our knowledge of animal husbandry and cattle subsistence strategies at Great Zimbabwe.

Brain (1974) analysed faunal remains from the Hodges Midden on the southern slope of the Hill Complex at Great Zimbabwe. The bulk of the faunal assemblage was identified as cattle (minimum number of individuals = 1330). Only 25 individual sheep/goats and 10 individual wild animals were recovered. Thus, 98% of the entire assemblage was identified as cattle. Of these, 56% were young animals without third molars. Brain (1974) interpreted the absence of M3s as an indication that they were in the early stages of formation, so that the crowns were not yet mineralized enough to resist diagenesis. 78.6% of the cattle at Great Zimbabwe were killed before the age of 30 months. Just over half of these had second molars not yet in full wear, so were probably no more than 18 months old. The dominance of very young cattle was consistent with the hypothesis that the hilltop was occupied by the elite. Thorp (1995) went on to investigate the age class distribution of fauna from major Late Iron Age sites in Zimbabwe, finding that most cattle in southern Zimbabwe were slaughtered as adults in the range of 18-30 months of age. The high proportion of very young cattle at the Hill Complex at Great Zimbabwe differed from this pattern. Thorp (1995) suggested that patterns of behaviour like those described in Venda ethnography where visitors were allowed to select an animal for slaughter, might account for this. An alternative explanation is that a young animal might have been selected if only a small group of people needed to be fed on the hilltop (Thorp, 1995). More recent faunal analysis from a larger distribution of excavated areas by Chiripanhura (2018) found that both young and old cattle were recovered from elite and commoner areas of the site. One likely explanation for this is that elite and commoner groups participated in meat-sharing practices as documented in the ethnographic record (Pwiti et al., 2013). This practice would result in the same animal being distributed across the site, leading to the skeletal distribution we see in the archaeological record.

Barker (1978) pointed out that the very young cattle recovered from the elite areas at Great Zimbabwe did not constitute breeding herds and therefore must have been taken from larger breeding herds for consumption by the elites. Thorp (1995) suggested that evidence of a few older individuals in middens associated with walled areas of the site indicated that there may have been breeding herds nearby. The most likely scenario for this is cattle paid as tribute by rural peasant communities to the centre of power (Sinclair, 1987). Indeed, the politically strong elites at Great Zimbabwe had very large herds of cattle, but there is little information about where the herds were kept and what pastured

were utilised. These factors must surely have played a significant role in the management of land and territories within the Zimbabwe State.

Researchers interested in cattle management at Great Zimbabwe have proposed that the most likely strategies would have involved seasonal movement of herds (i.e. transhumance) (Garlake, 1978; Bannerman, 1982; Sinclair, 1987). The reasons for proposing this are first, the fact that keeping large herds at Great Zimbabwe for prolonged periods would result in environmental degradation, so careful management of the pastures would have been needed. Second, heterogenous types of grazing in close proximity to each other would maximise seasonal nutrient intake of the herds. This hypothesis has never been empirically tested but transhumance is a very common herd management strategy used globally amongst prehistoric as well as modern-day herders. This becomes particularly beneficial during drought periods.

The clustering of smaller sites just below the edge of the plateau and the scarcity on the central plateau is consistent with the transhumance hypothesis (Garlake, 1978) (Figure 2.17). Garlake (1978) reported 33 Zimbabwe-type sites (evidenced by stone walling) within 10 miles of Great Zimbabwe, i.e. within daily walking distance. At the time of his research, none of these Zimbabwe-type sites lay within areas infested with tsetse-fly (Garlake, 1978), however more recent surveys show Zimbabwe-type sites existing in contemporary tsetse-fly zones (see Figure 2.20). See section 3.3.3 for a discussion of the distribution of tsetse-fly in prehistoric and modern-day Zimbabwe. The location on the edge of the plateau would make the seasonal alternation of grazing between the plateau and the lowveld (transhumance) plausible. Sites inside the areas infested with the fly would have been smaller, seasonally used sites and therefore poorly preserved (Barker, 1978) which might explain why they have not attracted much research.

In Mozambique, the Late Iron Age Zimbabwe-type site of Manekweni (Garlake, 1978; Barker, 1978) yielded a faunal assemblage very similar to that at Great Zimbabwe, in that young cattle were being slaughtered (Barker, 1978) and the age profile did not represent a breeding herd. The environment around Manekweni would have provided good water and pasture during the summer, but poor graze during the dry winter months, so that herds would have had to be taken elsewhere. Further, Manekweni is in a tsetse-fly zone and it therefore seems unlikely that cattle were kept there consistently throughout the year (Barker, 1978). It is more likely that male animals were brought in from elsewhere as and when needed for slaughter.

Tsetse flies carry trypanosome parasites which transmit the disease nagana in cattle, or sleeping sickness in humans. Nagana is often fatal to cattle and is very prominent in the dry savanna regions. Due to the fatality of the disease, it has very likely shaped the timing and the path of the spread of cattle through sub-Saharan Africa (Gifford-Gonzalez, 2000). Animal husbandry practices amongst early herders in southern Africa were also limited to areas where the fly was not present. Decisions on where to herd cattle can be complicated by the tendency of tsetse-belts to expand and contract over short time periods. In Uganda in the first half of the 20th century, tsetse-fly spread by as much as 150km in 50 years (Deshler, 1960; Lambrecht, 1964). Factors which influence the migration of the tsetse belts are amount of rainfall, changes in vegetation and fauna and bush clearing- all of which affect the suitability of the habitat for the fly. The presence or absence of cattle in the archaeological record may be a good indicator of the extent of tsetse-fly in the more distant past, assuming that people did not have adaptation strategies to overcome tsetse. Before much archaeological work was conducted in dry-savanna areas, Garlake (1978) used data from 1896 to map the maximum extension of the tsetse-fly at that time (Figure 2.20). It is likely that these areas may not have been clear from the fly continuously, however, they were not so infested that the areas had to be abandoned completely. Plug (1989) found presence of cattle in the Kruger National Park (north-east of South Africa) suggesting the Letaba, Olifants and Sabi rivers were clear of the fly during the 8th and 9th centuries. Similarly, Manyanga (2006) recovered many cattle in the Limpopo Valley dating from the 11th century to the 14th century showing the tsetse-fly was not prominent in this region around this time either. While we don't have a very clear understanding of the past distribution of tsetse, it must have been an important factor in Iron Age peoples' decisions about where to pasture their herds.

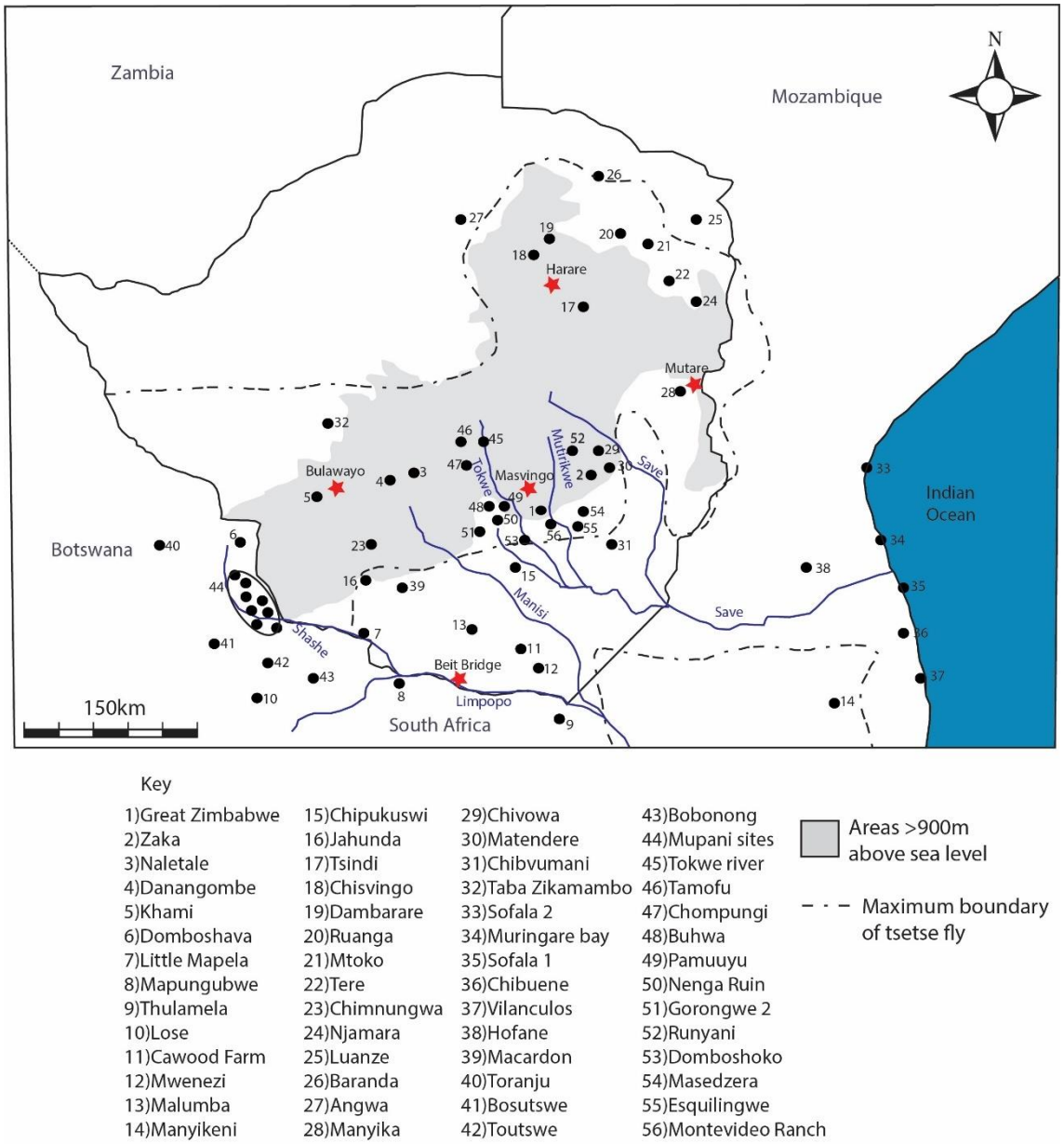


Figure 2.17: Map of *zimbahwe* in relation to tsetse-fly zone (established by Garlake, 1978) Drawn by M.House.

2.5.4 The decline of Great Zimbabwe

By AD 1450, the influence of Great Zimbabwe in long-distance, trans-oceanic trade had declined significantly (Pikirayi, 2001; Pikirayi 2006). Early studies proposed that, by the mid-fifteenth century, the scarcity of occupation of the Hill Complex meant that the site must have been abandoned (Garlake, 1973; Huffman, 1991). We now know that occupation continued into the mid-sixteenth century, as shown by the presence of blue-on-white porcelain from the valley enclosures (Collett et al., 1992), and even into the

seventeenth century (Chirikure et al., 2018b). There are two main hypotheses to account for Great Zimbabwe's decline in influence in the region. First, that the population at the site was so large that it negatively impacted the carrying capacity of the area and became unsustainable, forcing inhabitants to move elsewhere. Second, that Great Zimbabwe's sphere of influence became over-extended, allowing breakaway populations to form their own units and eventually compete for domination of the trade networks, choking Great Zimbabwe out. Each hypothesis will be discussed in turn.

It has been suggested that plant diversity around Great Zimbabwe has decreased due to prolonged harvesting of wild plants in pre-historic times (Bannerman, 1982). However, it is more likely that this is due to the management policies employed by the monument custodians (Ndoro, 2001). Even at the lower end of the range of population estimates, the firewood requirements of 11 000 people living at the site at any one time would have destroyed the woody vegetation within easy reach of the settlement areas. Large herds of animals would have had a disastrous effect on grazing land, and clearing of natural vegetation for agricultural fields would have led to soil erosion (Bannerman, 1982). If the landscape was no longer able to support the large population at Great Zimbabwe, people would have moved to other areas in search of opportunities (Huffman, 2007). However, evidence of long-distance movement of resources such as firewood show that people developed strategies for coping with environmental degradation (Chikumbirike et al., 2016).

Pikirayi (2001) points out that we should avoid environmental determinism, and that the decline of Great Zimbabwe would have involved social, economic and political factors as well as environmental ones. In the mid-fifteenth century, gold extraction was practised widely in other areas of the Zimbabwe plateau. Pikirayi (2001) proposes this would have encouraged the ruling elite at Great Zimbabwe to attempt to extend their realm of control over greater distances. To monopolise gold mining, a level of force or domination by the Great Zimbabwe king would have been necessary. Centres in distant regions would have been set up and may have resulted in disruptive demographic and economic shifts. If breakaway groups developed their own states in hinterland areas, this would ultimately have made Great Zimbabwe less important (Pikirayi, 2001). This scenario is supported in the archaeological record by the large number of fourteenth century sites in Botswana (Van Waarden, 1998), northern Zimbabwe (Pwiti, 1996) and south-central Mozambique (Garlake, 1978; Sinclair, 1987). Ingombe Ilede in Zambia (Pikirayi, 2017b) is a good

example of a site which probably had connections with Great Zimbabwe during its prime, but in the mid-fifteenth century shows a sudden increase in exotic trade goods such as glass beads as well as gold and copper objects. The implications of this are that Great Zimbabwe would have lost its significance as an economic trading hub to other new centres.

2.6 Description of context of material used in this study

This study utilises cattle remains from four excavation areas at Great Zimbabwe (See Figure 2.18 for location of excavation areas). The stratigraphy, radiocarbon dates and associated material culture will be discussed for each in turn. All four excavations were midden deposits encompassing time periods between AD1300 and AD1600. All but the Hodges Midden were excavated in 2017 (Chirikure et al., 2018b).

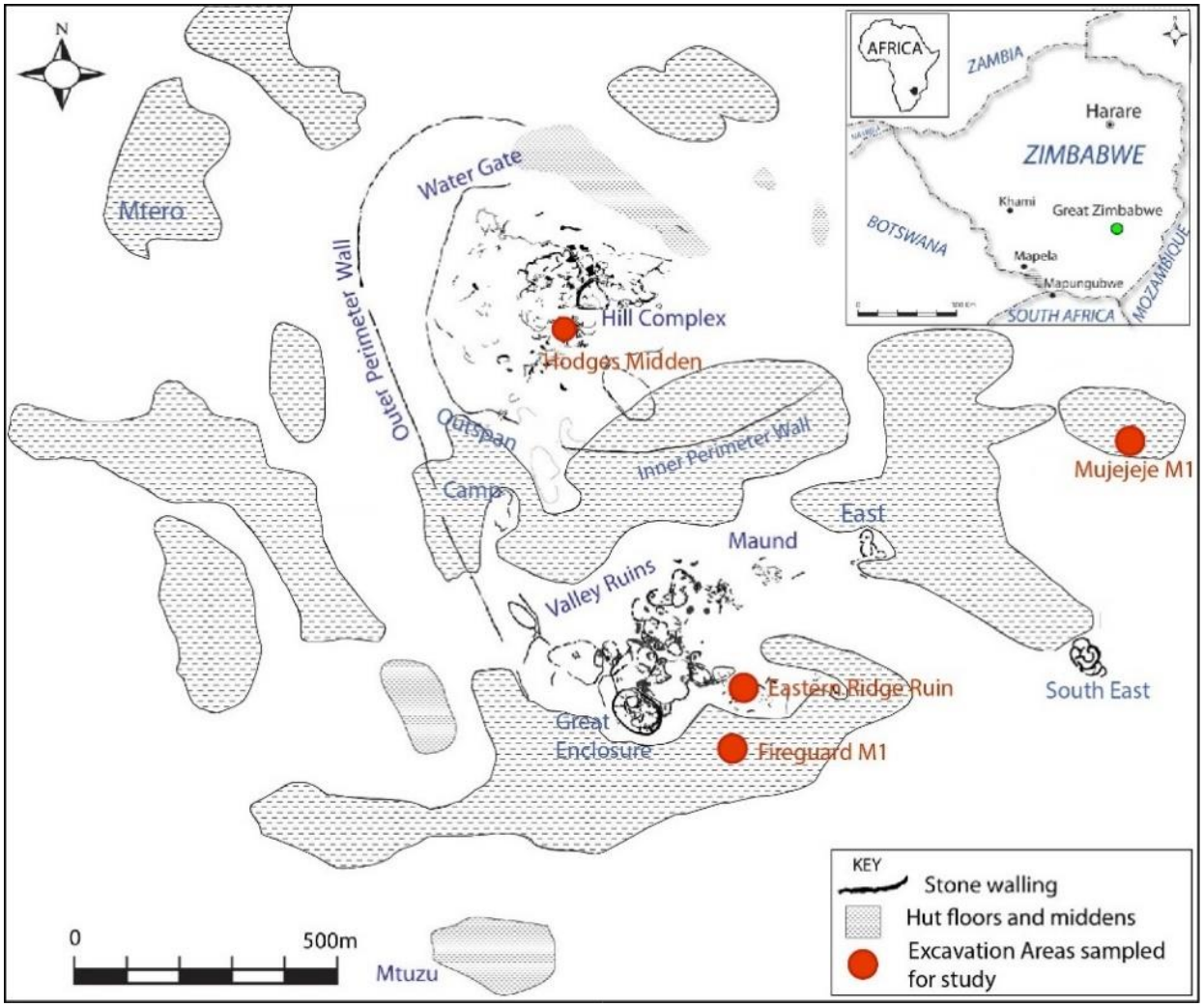


Figure 2.18: Locations of excavations at Great Zimbabwe yielding cattle teeth analysed in the thesis (modified after Chirikure et al., (2018b)**)**

2.6.1 Eastern Ridge Ruin Midden

Formerly known as the Mauch Ruin, the Eastern Ridge Ruin is located on the eastern end of the Valley Enclosures. A 2 X 1 trench was excavated on a midden about three metres away from the drystone wall enclosures (Figure 2.19). to enable comparison of material culture recovered from different areas across the site. The excavation reached sterile layers at a depth of 180 cm. The excavation yielded cattle remains, a gold pellet, crucibles, glass beads, and local pottery. The midden was dated to between the 14th and 15th centuries.

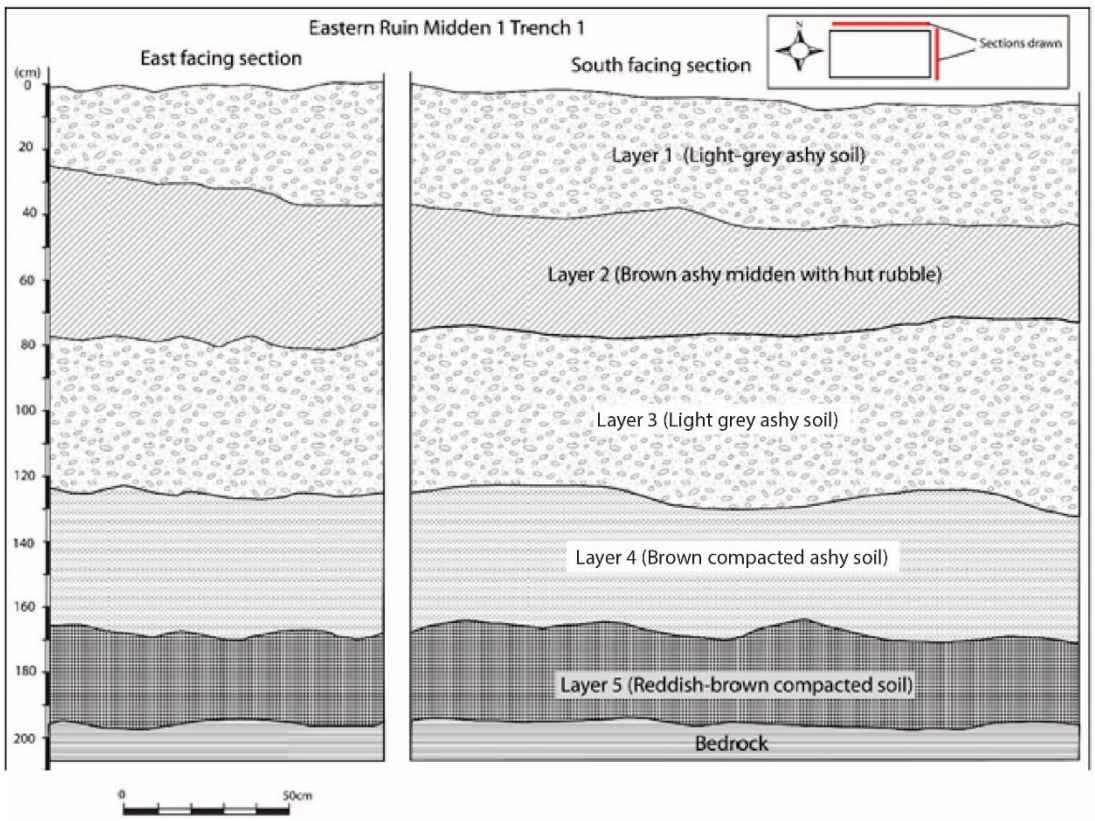


Figure 2.19: Section drawing of Eastern Ridge Ruin Trench 1 (drawn by Dr Foreman Bandama)

2.6.2 Mujejeje Midden

In the eastern unwalled area of Great Zimbabwe, three trenches were sunk at the location shown in Figure 2.18. This area is adjacent to a famous quartz vein known as Mujejeje. One trench was located on the edge of a borrow pit which had revealed hut floors, the other two trenches were in middens associated with houses to the north and east of the first trench. Maximum depth for all trenches was 60cm (see Figure 2.20). All trenches yielded metal objects, period IV ceramics and faunal remains (Chirikure et al., 2018b).

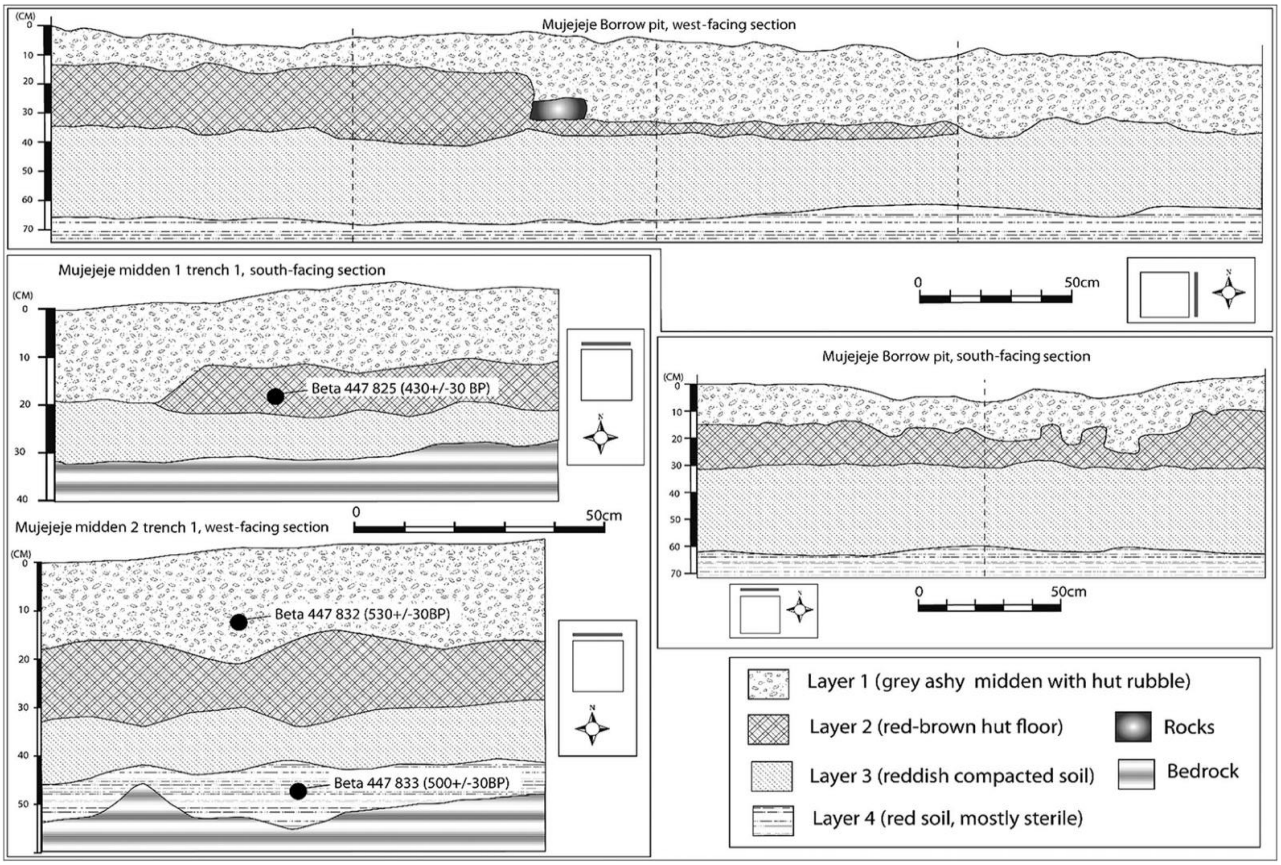


Figure 2.20: Section drawings of Mujejeje excavations (after Chirikure et al., (2018b)**)**

Three radiocarbon ages were measured and calibrated using OxCal v4.3.2 at 95.4% probability, SHCal13. Layer 2 midden 1 trench 1: 430±30BP; *cal AD1452-1496* (Beta 447 825)*;* Layer 1 midden 2, trench 1: 530±30BP; *cal AD1420-1442* (Beta 447 832) and Layer 4 trench 3: 500±30BP; *cal AD1435-1451* (Beta 447 833) (Chirikure et al., 2018b).

2.6.3 Fireguard Midden

The fireguard midden was a 2m x 2m excavation to the south-east of the Great Enclosure. Low stone walled enclosures were approximately 50m to the north of the trench. This trench too reached a maximum of 60cm in depth (See Figure 2.21). It yielded Period IV ceramics, two gold beads, glass beads, faunal material and more than 50 fragments of crucibles with gold droplets contained within the slag (Chirikure et al., 2018). One radiocarbon age was measured:460±30BP cal *AD1446-1463* (95.4% probability, SHCal13) (Beta 447 827).

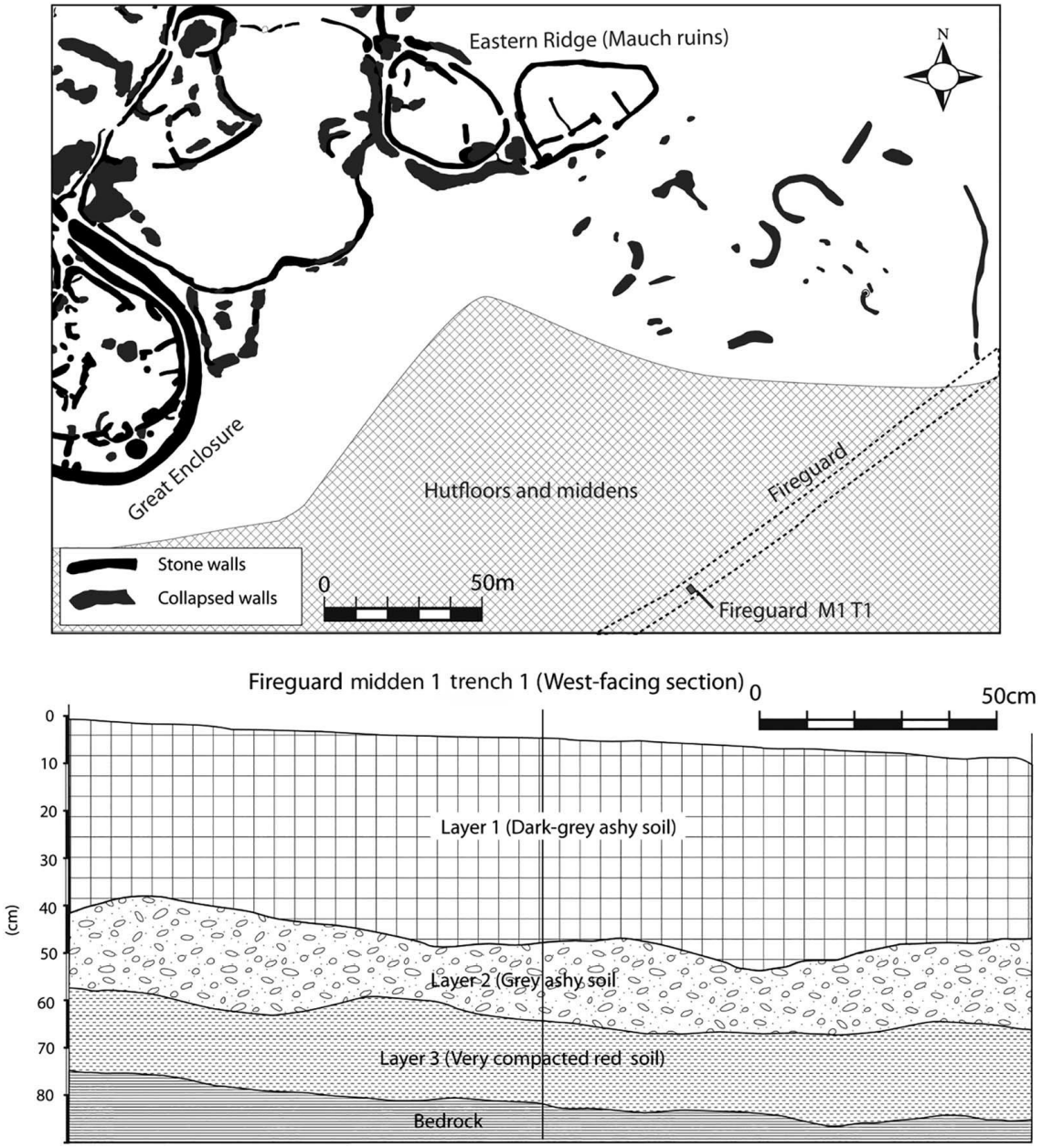


Figure 2.21: Plan of Fireguard Midden and section drawing (after Chirikure et al., (2018b))

2.6.4 Hodges Midden

In 1971 and 1972 Lillian Hodges excavated a talus slope along the south western edge of the Hill Complex in eight horizontal steps. The excavation did not reach bedrock (See Figure 2.22). This area was chosen for excavation because of the large quantities of faunal and other remains protruding out of the talus. The material excavated consisted of granite sand, interbedded ash lenses and red *daga* from hut floors. Large quantities of food waste, ceramics and other occupational debris were recovered, most of which was rubbish

disposed of by being thrown off the Hilltop. For the purposes of this study, different contexts of teeth from this excavation have been radiocarbon dated. These results are presented in Chapter 6.2. Ceramic analysis by Huffman shows that the material dates to Periods III and IV (Brain, 1974) and thus was discarded during the most intensive occupation at Great Zimbabwe. The material is housed at the Zimbabwe Museum of Human Sciences in Harare, Zimbabwe. The fauna was identified and described by Brain (1974). His findings are summarised in section 2.5.3.

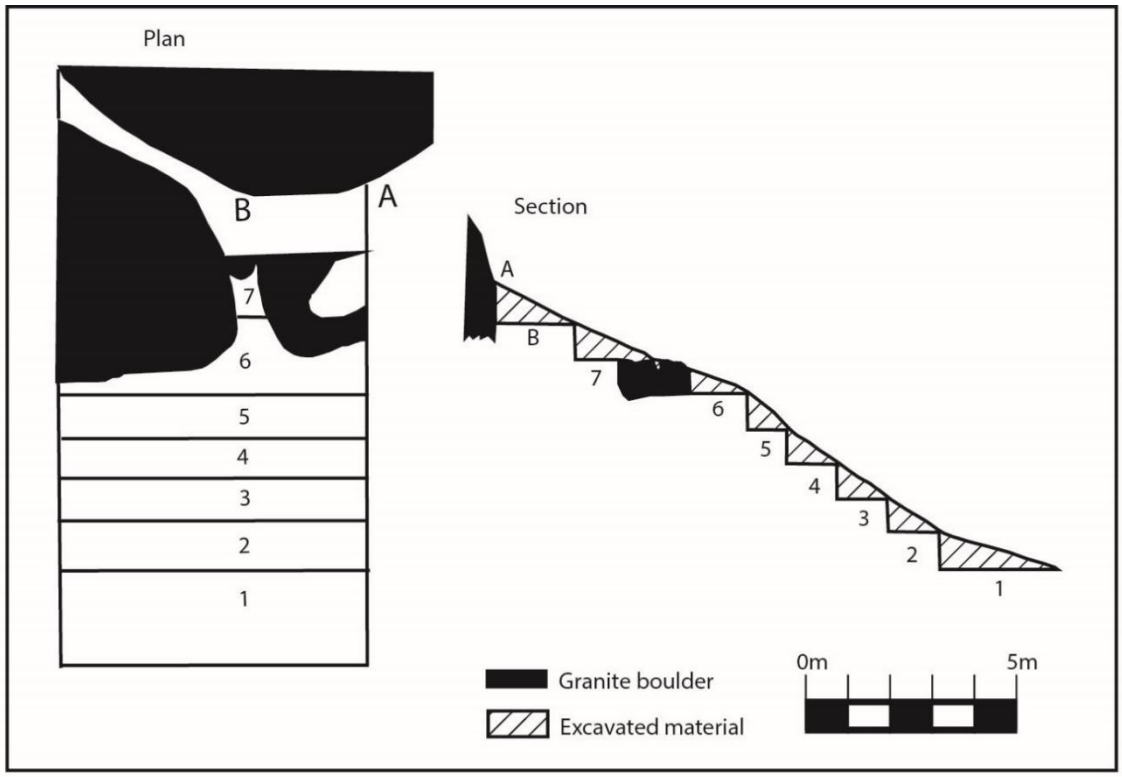


Figure 2.22: Plan and section of Hodges Hilltop excavation (after Brain (1974)**)**

2.7 Summary

Great Zimbabwe is an extremely complex site which was occupied at varying scales of intensity from AD300 until the recent historical period. Recent excavations have refined the chronology and settlement history of the site through radiocarbon dating and material culture analysis. Importantly, the day-to-day lifeways of the people who occupied the site have not been well researched. A primary determinant of where herders prefer to keep their cattle is the type of vegetation available. This is dependent on rainfall and geology.

High rainfall zones (e.g. the immediate vicinity of Great Zimbabwe) are associated with leached, sandy soils and perennial moist savanna vegetation whilst low rainfall areas (e.g. the Lowveld to the south of Great Zimbabwe) are associated with less leached, clay soils with annual nutritious dry savanna-type vegetation. These characteristics would have been key influences in herd management strategies amongst prehistoric herders. The presence of these very different environments in relatively close proximity to each other has led to hypotheses about seasonal use of the landscape around Great Zimbabwe (Garlake, 1978; Bannerman, 1982; Sinclair, 1987). These have thus far proved difficult to test, but differences in rainfall patterns, soil types and vegetation in the northern and southern regions of the study area mean that there may be detectable differences in the stable C, N, O and Sr isotope ratios of vegetation consumed by domestic stock. The isotopic composition of animal remains may allow us to identify where on the landscape the animals were grazing or browsing, and to draw conclusions about Iron Age herders' use of the landscape. This provides an opportunity for the first time to empirically test some of the hypotheses which have been proposed. The next section reviews why cattle are so important amongst Shona societies and explores animal husbandry practices used today in southern Zimbabwe.

Chapter 3: The importance of cattle in precolonial African societies with special reference to southern Bantu-speaking groups

3.1 Introduction

This section provides a synopsis of the social and economic value of cattle, highlighting why the herd management of cattle, specifically, was chosen for this study. Given their importance, the ethnographic record will be sourced for strategies of how these animals are herded in different ecologies of the study region. There are major differences in resource availability and restrictions in movement existing today that did not exist in the archaeological past. With these differences in mind, we can provide some hypotheses for possible scenarios of ancient cattle management strategies.

3.2 The importance of cattle

"A man without cattle in Shona society is like a house built on sand or a house built of cards which soon crumbles."

Fidelis Bere-Chikara (Kileff and Kileff, 1970).

3.2.1 The social roles of cattle

Cattle form an essential component of Shona culture as a connection to the ancestors, in ritual processes associated with death and in bridewealth transactions. The many social and symbolic roles of cattle in Shona societies have been well studied by ethnographers and anthropologists (Gelfand, 1958; Kuper, 1982). This section reviews our understanding of the social and economic roles of cattle in Shona societies.

3.2.1.1 Cattle as links to the ancestors

Information collected among the Chaminuka group around Masvingo province in Zimbabwe showed that cattle can serve as a kind of protection for the family by the

ancestors (Gelfand, 1958). An example of this is the bull of the village (*gono remusha).* If the grandfather (*sekuru*) dies in a family, his spirit will want a beast to be named after him and given to him in tribute. This beast protects the whole family and is kept in the eldest son's kraal. Similarly, in a large family group, one bull will represent the grandfather of the whole family. In the bull's naming process, someone will fall ill and this means that the grandfather's spirit expects his *gono remusha*. The father will pour a ladle of water on a calf's back and if the sick person gets better, the calf has been accepted by the grandfather's spirit. This process is witnessed by relatives in the cattle kraal. The father will know when the *sekuru* expects his bull to be sacrificed, because either his bull will refuse to graze and fights with other cattle, or the same person who became sick during the naming ceremony will do so again. The bull will then be killed and the meat eaten (Gelfand, 1958).

3.2.1.2 Cattle in bridewealth transactions

Cattle play a vital role in exchanges between married families in the form of bridewealth. According to Kuper (1982, p. 8) "*the fundamental bridewealth rule was that marital rights in a woman were transferred against the payment of cattle*". During bridewealth transactions, the mother got a cow known as *mombe youmai. Mombe* is cattle (which can refer to cow, ox or bull) and *mai* is mother. This cow is given by a man to his mother-in-law when he marries her eldest daughter. An example of this in information collected from south-eastern Zimbabwe showed that once the bride and groom are married, a second cow may be given to the wife's mother (if the daughter has been confirmed to be a virgin). This cow is called *mombe yechimanda* and is granted to thank the mother in law for preserving her daughter's virginity. If the husband wants to marry a second wife, he must give the first wife, who is the most important in the household, one cow. In southern Bantu societies, if the wife dies or is unable to have children, the wife's family must either give back the *mombe youmai* or provide another wife for the husband (Kuper, 1982; Shenjere-Nyabezi, 2016).

3.2.1.3 Gender and cattle

Most studies of cattle have focused on the way they empower men socially, politically and economically (Kuper, 1982; Huffman, 1982, 2001). Women are usually included in the discussion only in terms of bridewealth (Luedke, 2004). The basic division of labour too, separates men and women, whereby men are associated with pastoralism and hunting, and women with agriculture and gathering. However, the separation of women and cattle is sometimes more fluid. Men sometimes assist women in ploughing the fields and mostly use cattle for this (Shenjere-Nyabezi, 2016).

Once the wife has acquired the cattle through bridewealth transactions, her cattle can either be sent to her brother's household to be looked after on her behalf, or she may keep her cattle in her husband's kraal. In either case, the cattle cannot be used without her permission, and will not be used for any marriage transactions. Cattle owned by a woman can be used for milk, labour or slaughtered for her children if she wishes. If any of the cattle are slaughtered they must be replaced, otherwise the mother's spirit will avenge the household (Shenjere-Nyabezi, 2016). Cattle owned by men are more regularly used for slaughter and marriage transactions and this may result in female-owned cattle outnumbering male-owned cattle within a household (Shenjere-Nyabezi, 2016).

3.2.1.4 Cattle as an indicator for settlement layout

Ethnographic data has proven useful in interpreting the use of space in archaeological sites. A combination of Tswana, Pedi and Sotho ethnographies was used to identify principles of spatial organisation within homesteads of Bantu-speaking societies which use cattle for bridewealth (Kuper, 1982). There are two distinct separations. Firstly, centre and sides, which orders kinsfolk and wives and secondly, left and right, which order wives by seniority. There is some degree of variation, perhaps owing to differences in ethnicity, however the same basic spatial layout applies to both Nguni and Sotho-Tswana societies. Huffman (1982) effectively applied this basic settlement layout, the "Central Cattle Pattern (CCP)", to the archaeological record in southern Africa. In this layout, cattle were seen as occupying the physical and symbolic centre of all communities which used cattle for bridewealth in southern Africa.

This spatial settlement layout provided the basis for one school of Iron Age archaeological interpretation (Huffman, 1984, 1993, 2001; Whitelaw, 2012). According to Huffman (1982) there are four major characteristics enabling recognition of the CCP in the archaeological record. First, there is a central cattle byre that also contains grain bins and elite burials. Second, the men's court is located next to or inside the cattle byre. Third, the houses are arranged in an arc around the byre with the principal house upslope and to the back of the byre. Lastly, activities within houses are separated according to the principle that the right-hand side is allocated to men and male activities, while the left is allocated to females. Huffman (1982) has argued that many archaeological sites conform with this spatial layout. The location of cattle in the centre of the settlements of these societies vouches for the importance of cattle within these societies' worldview. This spatial model has been strongly critiqued by archaeologists on the grounds that there is a degree of evidence for the CCP in the recent past (post-AD1400) but is more ambiguous in the deeper past (Lane, 1994, 2005; Maggs, 1994; Calabrese, 2000). The model has also been critiqued by historians for not considering the context of collection of the ethnographies on which the model is based (Hall, 1987; Lane, 2005; Badenhorst, 2009; Pikirayi and Chirikure, 2011; Chirikure et al., 2018b).

3.2.2 The economic roles of cattle

Cattle and crop production are intricately linked amongst contemporary herders in southern Africa. For example, cattle provide transport, manure for fertilizer and draught power for tilling the land to increase crop production. Crops contribute to livestock production as animals consume crop residues after the harvest (Barrett, 1992). Furthermore, cattle provide milk, hides and horns and are sometimes exchanged for other goods (Barrett, 1992).

3.2.2.1 Draught power

Cattle are today, used for draught power in the form of ploughing fields: not only those of the cattle owners, but other fields too[4]. They are also used to pull scotch carts to carry firewood and for general transport. The importance of different types of cows used for draught (i.e. oxen, steers, bulls or cows) varies considerably from place to place (Munn and Zonneveld, 1990; Scoones, 1991; Chimonyo et al., 1999). Importantly, if cattle are used for draught, they will drop dung as they move through the fields (see Figure 3.1), increasing the $\delta^{15}N$ value of the crops grown on that field. This is discussed further in section 4.3.2.1.

Figure 3.1: Oxen being used as draught power to plough a field near Nemanwa Ruin, Masvingo (photo taken by Elton Sagiya)

Frequency of draught by oxen is constrained by the growing season of crops and access to implements such as ploughs and scotch carts (Barrett, 1992). A span of oxen can plough up to 0.4ha per day (Munn and Zonneveld, 1990).

[4] There is no evidence that pre-colonial farmers in southern Africa were using animal-drawn ploughs. There is only evidence of hand-tilling fields by using iron implements such as hoes.

3.2.2.2 Milk production, meat and bleeding

Cows' milk is the primary dietary product consumed by pastoralists and the amount of milk produced changes with environmental stress and periods of lactation. The use of cows for draught decreases their fertility and therefore milk production (Goe, 1983; Matthewman, 1987). The amount of milk taken from the cow varies from household to household and is therefore indicative of management practices. Tiffen (1987) has found that yields can be around 300 to 350kg of milk per cow during the whole period of lactation, which may last up to 150 days.

Slaughtering is the secondary dietary use of cattle. Amongst pastoralist societies this is emotionally and symbolically charged, and restrictions are set in place as to when it is appropriate. Cattle are seldom slaughtered until milk is short, e.g. during droughts, and slaughter is necessary to ward off starvation (Dahl and Hjort, 1976). In addition to drought, disease, rain rituals and feasts are also reasons to slaughter cattle (Gelfand, 1958). Productive female cows are very seldom slaughtered, and bulls are rarely slaughtered just for food.

Bleeding is the tertiary dietary use of cattle and can be conducted on live or recently slaughtered animals (Barrett, 1992). It is common practice to bleed an animal whilst it is alive and the blood of a slaughtered animal will be consumed during dry periods when milk is scarce (Dahl and Hjort, 1976).

3.2.2.3 Herd Composition

The ratio of new-born males to females is 1: 1 but amongst adult cattle, it can be up to 1:100. Bulls that are not needed may be castrated and used for blood or saved for a ritual ceremony. The female cattle are usually kept, and this builds the herd size. In recent times, bulls are typically slaughtered at the age of four to five years, and cows at the point at which they are no longer productive (Dahl and Hjort, 1976).

In communal areas of Zimbabwe, a 'typical' herd of cattle comprises 45-50% cows and heifers, 35% bulls and oxen and 15-20% calves (Barrett, 1992). On average, the age of first calving is around four years (Steinfeld, 1988; Scoones, 1995). At about ten years, the cows become unproductive and are usually sold or slaughtered (Scoones, 1995).

Functional questions pertaining to the number of cattle and/or small stock needed to sustain a population, grazing strategies during times when grass was plentiful, as well as times of drought and the types of vegetation containing the most nutrition for domestic stock have not yet been addressed specifically in relation to the Zimbabwe Culture.

3.3 A review of contemporary cattle herd management strategies in southern Zimbabwe

A 2006 survey showed that at the time of the study, about 70% of the population of Zimbabwe was dependent on farming for a livelihood (Note that there have been major changes since this publication as a result of land reclamation)(Gambiza and Nyama, 2006). There are four sectors of farming in the country: large-scale commercial, small-scale commercial, communal and resettlement (Gambiza and Nyama, 2006). 74% of communal farmland is on infertile sandy soils in regions of low and erratic rainfall. Farmland also contains the highest human population density. The landscape and vegetation of southern Zimbabwe have changed substantially since the time when Great Zimbabwe was occupied. With these changes in mind, we can cautiously use the ethnographic present to develop scenarios which will provide possible ancient cattle management practices.

Contemporary herd management strategies in Zimbabwe are strongly influenced by the effects of colonialism on land ownership and distribution. From the start of British rule in the country in 1890, black people were forced to move out of fertile agricultural areas and into poor infertile communal lands. By 1914 white settlers (who made up 3% of the population) owned nearly 50% of land in the country, including all the best agricultural land. These effects of unequal distribution of land ownership continued into the recent past and by 1994, commercial farms with only five percent of the country's population owned 38% of all land, most of which was in Natural Region III. The remaining 62% of land (mainly in Natural Regions IV and V) was occupied by 95% of the population (Hamandawana et al., 2005). A consequence of this is that resources and mobility of herds are more restricted today than they were in the past. With these biases in mind, we can use contemporary herding strategies in order to compare them to the archaeological past.

There are approximately 4-5 million head of cattle in Zimbabwe with 89% found in communal areas (Mavedzenga et al., 2006; Ndebele et al., 2007). Communal herds consist

of "indigenous" breeds, mainly Mashona, Tuli, Sanga and Nguni types, which are derived from precolonial cattle, or crossbreeds of predominantly indigenous blood. Indigenous cattle have the advantages of hardiness, high fertility, high tolerance to disease and heat and low feed requirements (Moyo et al., 1996; Khombe, 2002; Mpofu, 2002; Assan, 2013). Most modern-day cattle, goats and sheep are pastured on natural vegetation (as opposed to supplementary feeding).

Successful cattle herding requires consideration of a variety of factors, including optimal (often seasonal) scheduling of resource management during times of drought, coping with diseases such as that carried by tsetse-fly, and how best to integrate cattle into other aspects of farming practice, e.g. foddering and manuring. Herding practices differ according to the environmental context, especially amount of rainfall and quality of vegetation. Table 3.1 shows seasonal pasturing strategies implemented in recent times in different vegetation biomes [Data compiled from (Scoones, 1995)].

The extent to which it is necessary to move cattle seasonally differ between dry zones (<600mm rainfall per annum) and wetter environments (>700mm rainfall per annum). In dryland areas, several studies have indicated that it is vital for livestock to be able to move freely between vegetation types in order to obtain adequate nutrients (Scoones, 1989, 1991, 1994). This section reviews cattle management strategies in the higher rainfall sourveld area of Great Zimbabwe and that in the drier sweetveld areas of lowveld Zimbabwe.

Table 3.1: Resource use by cattle over different veld types in the Mazvihwa district of south-central Zimbabwe (rainfall ca. 700mm p.a) (Scoones, 1995)

	Cropping season (November to March)	Early Dry Season (April to June)	Late Dry Season (July to Oct)
Sandy soil (sourveld)	Upland grazing (43%) [5]Dambo grazing (49%)	Upland grazing (8%) Field grazing (60%) Contour grazing (29%)	Dambo grazing (31%) Upland grazing (31%)
Clay soil (sweetveld)	Upland grazing on clay soil (42%) Riverbank grazing (41%)	Arable grazing: graze contour ridges and off crop residues (100%)	Browze, arable grazing and maize residues from homesteads (100%)
Edge Zone (Mixedveld)	Sandy soil upland graze (45%) Drainage line graze on clay soil (36%) Dambos on sandy soil (7%)	Contour ridge graze (33%) Crop residue (24%) Upland graze on sandy soil (13%) Drainage line (24%)	Sandy soil only: Arable land (3%) Drainage lines (8%) Contour bunds (9%) Dambos (13%) Home sites (20%) Upland graze (45%)

[5] Dambos are isolated shallow wetlands which provide good seasonal grazing

3.3.1 Cattle herding within sourveld vegetation around Great Zimbabwe

In September 2017, there were 12 000 head of cattle in the areas surrounding Great Zimbabwe (Mr Zvoushe, local vet in Nemamwa Growth Point, pers. comm. 2017). The carrying capacity around Great Zimbabwe is 15 cattle per hectare with overstocking a growing problem. The area around Great Zimbabwe is today free from tsetse-fly but subject to sporadic outbreaks of foot-and-mouth disease, spread by cattle mixing with wild animals such as buffalo. Foot and mouth prevention measures involve a ban on cattle moving between the highveld and the lowveld (also known as the 'red zone'). Communal cattle in this area are free-range grazers, roaming around during the day and penned in the cattle kraals at night. During drought, herders buy supplementary feed for their cattle, but this is very costly. Throughout the year the cattle drink from perennial rivers which are replenished in the rainy season.

The cattle remain in the area around Great Zimbabwe throughout the year and contrary to strategies implemented in drylands (as discussed below), there is no seasonal movement of the animals across the landscape (Mr Zvoushe, pers. comm. 2017). This lack of movement of herds in these wetter environments of the sourveld has been documented in other studies (Scoones, 1989, 1991). The fact that the animals do not move indicates that they are able to sustain their body weight in the dry winter months. This is likely from the small amounts of annual grasses which exist around Great Zimbabwe alongside the abundant perennial sourveld grasses (Gambiza and Nyama, 2000).

Today, agriculturalists use mixed farming strategies to maximise agricultural and livestock output. These include using cattle to plough land, using manure to fertilise soil, and supplementing feed with crop residues. These measures are effective in combatting intermittent adverse environmental conditions, for example, droughts, as experienced around Great Zimbabwe. Seinfeld (1988) showed that each household spread one to three tonnes of manure every year, 95% of it on maize crops. After a drought, such as that in 1992, this amount of manure may not be available (due to loss of cattle). Wolmer and Scoones (2000) reported two different strategies observed in the Ngundu village in Masvingo Province in Zimbabwe to obtain larger amounts of manure. One approach was to add grass and crop residue to the cattle kraal to be trampled into the manure, thus increasing the amount of organic-rich fertilizer which can be added to the fields. The second approach was for the farmer to leave the stubble after harvesting his crop *in situ*

and allow the cattle to graze the fields, fertilizing them at the same time. In semi-arid regions with richer, more fertile soils, manure is not added because it will "scorch" the crops (Wolmer and Scoones, 2000).

3.3.2 Cattle herding within sweetveld vegetation around southern Zimbabwe

In the semi-arid region of Matabeleland (south-west of Great Zimbabwe) seasonal utilisation of sweetveld and sourveld forms the basis of winter (dry season) and summer (rainy season) transhumance strategies (Prescott, 1961, Cobbing, 1976). This seasonal movement also coincides with the cropping season in sweetveld regions of south-western Zimbabwe (Madzudzo and Hawkes, 1996). During the rainy season from November to April, cattle grazed around the homestead. There was enough grass and water at this time of the year to remain in one area. At the onset of the dry season, in May or June, cattle were set onto the fields which had just been harvested. At that time of the year, grass quality had deteriorated, but water was still available. The crop residues provided enough nutrients for the cattle where grass cover was not adequate. In the late dry season, from August to October, cattle were moved away to graze at the *lagisa*[6] area anywhere from 20 to 100 kilometres away from the homestead.

As some households could not afford to set up temporary homesteads at the *lagisa* area, this strategy was limited to richer households (Madzudzo and Hawkes, 1996). Differences in cattle ownership, location of herders, availability of grass and water, the speed with which harvesting is completed and the availability of labour and financial resources played significant roles in whether herders utilised the *lagisa* or not. In fact, 57% of all cattle were kept around the homestead year-round. The herders who did utilise the *lagisa* owned much larger herds, while those who did not use the *lagisa* did not find it economically viable to do so.

Sweetveld grasses are very sensitive to overgrazing. If overgrazing occurs, cattle need to incorporate an adequate amount of browse, which is relatively high in protein, into their diet (Gambiza and Nyama, 2006). One favoured browse plant is the shepherd's tree, *Boscia*

[6] *Lagisa (*also known as *muraka* in Botswana*)* is a form of transhumance practiced by groups in southern Africa. The *lagisa* is an area with good grazing and water owned by the community rather than one person. It is used seasonally by pastoralists who set up impermanent structures in which they live whilst their cattle graze on the sweetveld pastures. The *lagisa* is usually used in the dry season (Madzudzo & Hawkes 1996).

albitrunca (Cowling et al., 2004). Others include mubhondo (*Combretum apiculatum),* mupanda *(Lonchocarpus capassa),* mususu (burch tree) *(Terminalia sericea),* mopane (*Colophospermum mopane*) and mupwezha *(Combretum collinum)* (Scoones, 1994). Desirable features in deciduous browse species are early shooting of leaves (which occurs in September), palatability and high water content, which fluctuate with the time of year. These deciduous leaves fall to the ground in autumn and are likely included in the animals' diets as they eat the grasses during this time. The mupane and mususu were ranked as the highest importance in the region (Scoones, 1994). Figure 3.2 shows photographs of these leaves.

(a)  (b)  (c) 

Figure 3.2: Photographs of (a) mopane leaves, (b) shepherd's tree leaves and (c) burch leaves, all heavily browsed by cattle

As an adaptive response to herbivory, trees release secondary metabolites such as tannins and phenols. Larger quantities of these chemicals make browse less digestible (Cooper and Owen-Smith, 1985) and cause loss of appetite in the herbivores (Van Hoven, 1991). The tannin and phenol concentration in browse therefore has a direct effect on the amount of forage an herbivore can consume in a season. Makhado et al. (2018) showed that the removal of up to 10% of leaves from mopane trees did not increase the quantities of secondary metabolites produced by the plant. This makes mopane particularly good for browsing, because consumers will not suffer the negative effects of tannins.

Droughts can manifest in different ways, affecting crops and grass production differently, as well as varying on spatial and temporal scales. Farmers need to be flexible enough to adapt to these changes. Scoones (1992) studied inter- and intra-annual drought coping strategies amongst modern day herders, focussing on two major droughts in the 1980s. He analysed dip records from across the Zvishavane district and 385 cattle owned by 71 households in the Mazvihwa communal area (See Figure 3.3). He found that during years with normal rainfall (ca. 500mm) movement was an important part of cattle herding.

During drought years, herders moved their animals considerably longer distances. This large-scale movement is mainly because of the limitations of land availability due to privatisation (Scoones, 1992). Herders are forced to move their herds much longer distances than they may have in the past. During the first major drought, herders moved cattle away from the clay soil savanna to the sandy soil savanna. The animals also browsed more than usual. However, the sandy soil vegetation could not support the large influx of cattle and herders were forced to move the herds away either to the Mapanzure area and then beyond to the commercial farms in the Shurugwi district, or to the south east in Chiredzi (see Figure 3.3). These movements totalled approximately 60kms.

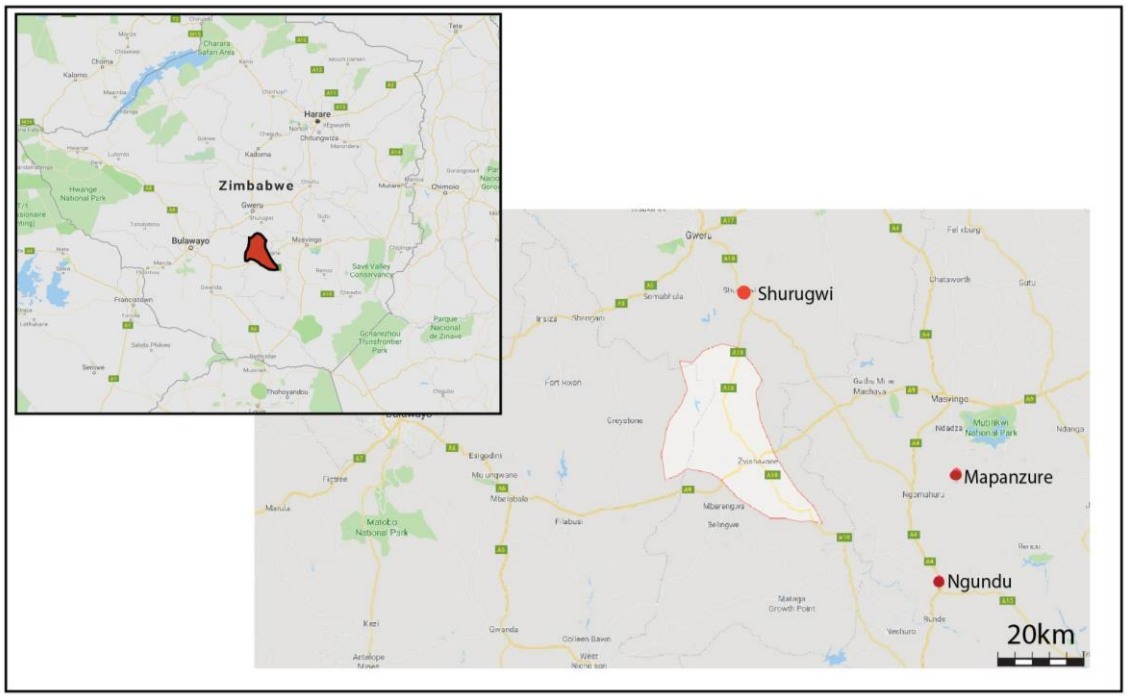


Figure 3.3: Location of villages mentioned in text (Zvishavane district highlighted in red)

3.3.3 Tsetse-fly

A major disease risk for cattle in Africa is animal trypanosomiasis, or *nagana*. These are protozoan parasites which are carried by various species of tsetse-fly and infect blood and tissues of domesticates. Of the various species of trypanosomes, the ones which are well-known to infect cattle are *T. congolense, T. vivax* and *T. evansi* (Connor, 1994). The tsetse-fly ingests the parasite from mammalian blood and the parasite continues its cycle of infection by migrating to the fly's salivary glands. Once the fly bites another mammal, the parasite is transmitted into the next animal. In domestic livestock, infection leads to fever,

anaemia and loss of condition and extreme weakness and death in the final stages (Pratt and Gwynne, 1977; Murray and Dexter, 1988). Sometimes cattle recover from these infections, but they continue to carry the parasite and symptoms may re-emerge. Infection of one animal may cause the whole herd to be infected. Tsetse-flies seem to prefer to bite cattle rather than sheep or goats. A study in Zimbabwe showed that the ratio of bites of cattle, sheep and goats was 500:5:1 (Connor, 1994). Sheep and goats, although infected by the same species as cattle, rarely develop the same level of symptoms and are less likely to die from the disease (Gifford-Gonzalez, 2000).

Tsetse-flies need shady, bushy environments to pupate, so animal trypanosomiasis occurs mostly in these types of environments (and most often in wild ungulates). Based on ecological characteristics suitable for tsetse-fly reproduction and historical records of presence of the fly, Garlake (1978) produced a map showing that tsetse-fly was likely to occur in southern and northern Zimbabwe, not on the plateau.

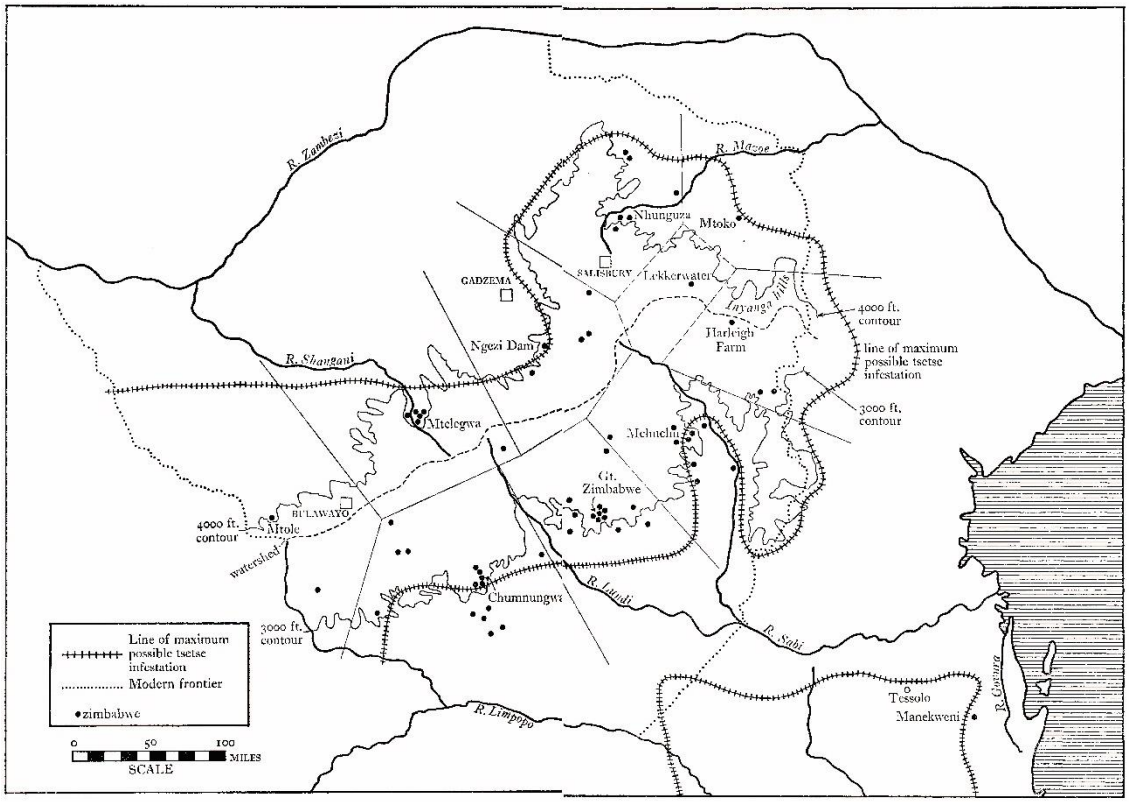


Figure 3.4: Garlake's (1978) map of the likely distribution of tsetse-fly in southern Zimbabwe based on environmental suitability

Contemporary pastoralists can manage the environment in order to inhabit areas infested with tsetse-fly. The Fulani in western Chad move their herds into tsetse-infested areas only

in the dry season when the fly is not dangerous (Stenning, 1959). Il Loita Maasai groups in Kenya burn bushy environments to prevent the fly pupating, ultimately clearing tsetse fly from large areas (Lamprey and Wallace, 1990). This is also observed in south-east Zimbabwe, where Gaza groups create a buffer zone by burning vegetation (Mavhunga, 2018). In an experiment to quantify how much smoke from cow dung and from mopane wood reduces the fly, Torr (2011) set up fly traps around cattle kraals and found that there was an 80% reduction in fly from the smoke. In the same experiment, it was found that cattle contained in a kraal with a high (1.5m), solid perimeter wall would have a reduced rate of trypanosomiasis infection. This is, however, dependent on the daily biting and infection rates. If they are high, then an 80% reduction is not significant. Tsetse-fly has also been cleared using extensive grazing and burning strategies in Tanzania (Kjekshus, 1977). In West Africa, smaller humpless breeds of cattle (N'Dama, Bambara shorthorn, and Baoule breeds) are known to be trypanotolerant breeds as they maintain their productivity during infection. This characteristic is a result of genetic mutations (Hanotte et al., 2003; Tijjani et al., 2019).

Seasonal use of the landscape is also a way to minimise risk of tsetse-fly diseases. For example, Zulu herders in the valleys of the Umfolozi and Hluhluwe Rivers moved their cattle to the highlands in summer when the fly was dangerous in the lowlands, and to the lowlands in winter when the fly was less active to do any damage (Mavhunga, 2018). Ndebele groups occupied hilltops from where they could see enemies approaching, and their cattle were safe from the fly. For short periods of the year, they could move their cattle into the lowlands to graze when the fly was not dangerous (Mavhunga, 2018). Because wild animals serve as a major reservoir of trypanosomiasis, eradicating wild animals from the immediate environment is another way to limit the spread of tsetse-borne diseases.

3.4 Summary and Gaps in Research

Herd management strategies in southern Zimbabwe require a deep knowledge of the vegetation, rainfall patterns and soil types of the landscape, as seen today in contemporary communal areas. The region around Great Zimbabwe is an isolated area of high rainfall supporting sourveld vegetation with patches of sweetveld on sandy soils. Today, the environment around Great Zimbabwe is favourable for crop production and pastoralism. Contemporary studies of adaptation to drought have revealed a range of possible responses.

The first is that during the dry winter months, pastoralists move their cattle herds to an area of water and good pasture, for example, from the sourveld to the sweetveld. This carries an economic cost such as paying a herder to look after the stock or moving the entire family to the new kraal and thus sustaining two households at once. A second option is for herders to remain in the sourveld (which also contains patches of annual grasses) and provide enough nutrition through the dry period by feeding crop residues and/or encouraging browsing. The disadvantage of this option is that the cattle may lose condition. The region around Great Zimbabwe contains good browse as well as graze and is situated a few kilometres away from areas of sweetveld vegetation, so that both options are viable herding strategies in most years.

Today, cattle herders around Great Zimbabwe allow their cattle to roam around the immediate vicinity of the site to graze year-round. They do not see the need to move their cattle to another area, because during winter drought, herders can supplement the herd's diet by using crop residues or buying feed if the patches of sweetveld grasses are insufficient. In addition, movement to the sweetveld vegetation to the south is unattractive due to the prevalence of tsetse-fly. However, this lack of movement may be a result of land tenure changes from 1893 onwards, and may not reflect the management practices which existed in the past.

It is worth noting here that all inferences about ancient herd management strategies at Great Zimbabwe have been based on the presence of large numbers of cattle bones, in combination with researchers' understanding of the ecology of the area. Hypotheses such as that of transhumance have not been empirically tested. Despite this, it has been proposed that during Great Zimbabwe times, transhumance was a major herd management strategy to maximise nutrient intake (Garlake, 1978; Bannerman, 1982). Modern day studies such as that of Scoones (1992, 1995) show that transhumance is an important strategy in semi-arid regions where seasonal movement of herds is vital for them to maintain their body weight through the dry winter. However, Great Zimbabwe is situated on the Zimbabwean plateau, and receives 1000mm of rainfall per annum. This is not a semi-arid zone and raises the question of whether transhumance was necessary in a relatively moist environment. If a large cattle population was being supported at the site, where were these cattle being herded and grazed? What kinds of strategies could be implemented to avoid overgrazing? If transhumance was a strategy, can we identify how far the herds were being relocated? Were these strategies implemented on a seasonal basis or only during droughts? The next

chapter will provide details of the principles of the stable isotope approaches used in this study and how they can be used to reconstruct herd management at Great Zimbabwe.

Chapter 4 Principles of stable light isotopes and their use as environmental and dietary tracers

4.1 Introduction

Stable isotope ratios enable archaeologists to trace flows of nutrients through food webs. In well-preserved archaeological remains, we can use stable isotopes to reconstruct past diets and environments (Fry, 2006; Sharp, 2007; Michener and Lajtha, 2008). The most powerful studies apply a range of different isotopic approaches to multiple consumer tissues, in order to extract maximum information. This chapter discusses the structure and growth of tooth tissues used in this study: enamel and dentine. It then outlines the principles of the naturally occurring variations in the ratios of isotopes used in this study, and what information we can gain by measuring them. Finally, the chapter reviews how other studies have used multi-isotopic data from serially sampled teeth to investigate movement and diet of animals through time and space.

4.2 Tooth morphology

In mammals, there are four types of teeth with specific functions and positions: the incisors, canines, premolars and molars. All have the same basic structure: the crown, which is covered by a layer of enamel, and the root, which is coated with cementum. Dentine comprises most of the volume of the tooth, making up the inner part of the crown and the root. The pulp chamber is located in the centre of the tooth and contains the nerves and blood vessels providing the tooth with nutrients (Ungar, 2010) (see Figure 4.1 for schematic diagram).

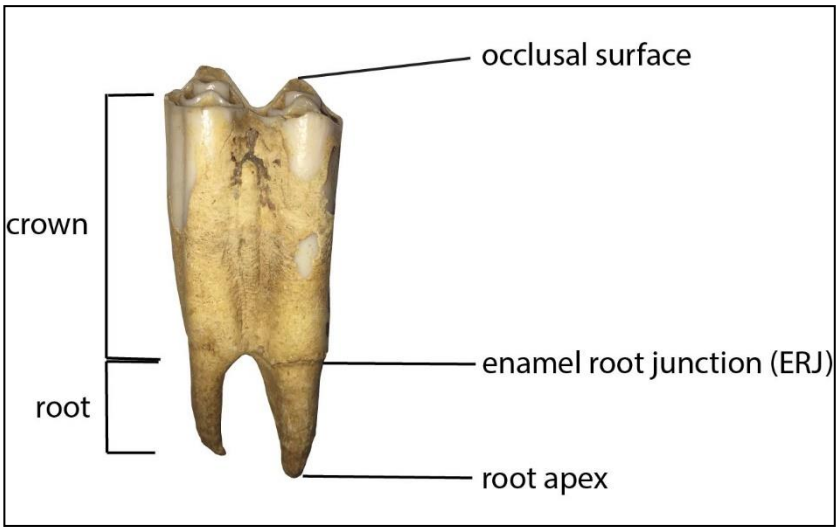


Figure 4.1: Major features of the surface of a *Bos taurus* lower second molar (photo by M House)

Tooth formation occurs in three stages: the bud stage, the cap stage and the bell stage (Brown et al., 1960; Hillson, 2005). The bud stage is the initial stage of tooth development in which the dental lamina forms from epithelial cells. The cap stage is the first sign of an arrangement of the cells, as lateral extensions of the bud begin to take the shape of a cap, forming dental papillae. The mesenchyme surrounds the developing dental papillae and condenses to form the dental follicle. During the bell stage, cell specialization occurs: the epithelium develops outer ameloblasts, which secrete enamel, and inner odontoblasts which secrete dentine. The future enamel and dentine form from what will become the occlusal surface and progress towards the root apex (Hillson, 2005).

Cattle are bovids, and thus their dental formula is 0.0.3.3/3.1.3.3. Cattle have high crowned ("hypsodont") teeth which have evolved to cope with an abrasive grassy diet. The three permanent molars in cattle form over the first three years of life. Second molars, studied in this thesis, begin to form one month after birth. The crown is fully formed by one year of age and growth is complete (closure of root apices) two years after birth (Brown et al., 1960; Hillson, 2005)) (Table 4.1).

Table 4.1: Permanent molar development in cattle (from Brown, 1960)

Development	First Molar (months)	Second Molar (months)	Third Molar (months)
Crown formation begins	In utero	1	9-10
Crown formation complete	2-3	12-13	23-24
Root formation complete	13	24-25	38

Dental tissues consist of inorganic and organic components. The inorganic component is nearly entirely made up of calcium phosphate minerals, mostly in the form of apatite. The organic component of dental tissues consists mainly of collagen, which is a fibrous protein also found in bone and cement (Ungar, 2010).

4.2.1 Dentine structure

Dentine is deposited in cone-shaped layers from the occlusal surface towards the root apex, thus the whole dentine body gains in width as it gains in length (Hillson, 2005). Pre-dentine is deposited by odontoblasts as a layer of unmineralized collagen-rich organic matrix in the initial stage of formation. Minerals in the form of hydroxyapatite crystals are then deposited in the final stage of formation forming a strong, stable dentine structure (Orsini et al., 2012).

Dentine is synthesised largely from dietary amino acids, although dietary carbohydrates and lipids can make a significant contribution (Howland et al., 2003). This tissue is made up of approximately 70% apatite, 20% collagen and other proteins and 10% water (Ungar, 2010). In addition to collagen, the organic phase also contains several non-collagenous proteins and proteoglycans, which make up about 10% of the organic material (Orsini et al., 2012). Unlike bone, dentine is not remodelled (Gage et al., 1989), and therefore provides a time series of tissue from the start of tooth formation at the occlusal surface to its completion at the root apex.

As a result of the cone-shaped deposition of dentine, sampling strategies that involve slicing the tooth horizontally, i.e. transverse sections, lead to time averaging. In cattle, horizontal subsamples 2 mm thick are estimated to be formed over approximately four months (Zazzo et al., 2006). Some studies have employed more sophisticated sampling strategies. These include sampling the innermost layer of dentine using a micromill, which

results in increased chronological control (Zazzo et al., 2006). However, it was found that even if an abrupt diet switch occurs, the stable isotopes of consumer tissue will not reflect the rapidity of diet switch because of the metabolic pool equilibration period (Jones et al., 1981; Ayliffe et al., 2004; Zazzo et al., 2006).

4.2.2 Enamel structure

Enamel is a mostly inorganic dental tissue found on the exterior of the crown of a tooth. Enamel is synthesised from blood bicarbonate and reflects the whole of an animal's diet: proteins, lipids and carbohydrates (Krueger and Sullivan, 1984; Passey et al., 2005). It consists of crystals of hydroxyapatite ($Ca_{10}[PO_4]_6[OH]_2$) packed into an organic matrix. Bioapatite contains carbonate ions (CO_3) substituted in the PO_4 position (Boyde, 1967; LeGeros, 1991, Balasse, 2002); carbonate is also adsorbed on to the surfaces of the apatite crystals. Enamel is extremely compact with large phosphate crystallites and little pore space. These characteristics make enamel less susceptible to diagenesis than dentine (Lee-Thorp and Sponheimer, 2003). It is usually the preferred tissue for studies of very old material (more than ten thousand years), or poorly-preserved material (Lee-Thorp et al., 1989; Quade et al., 1992; Fogel et al., 1997) . Enamel, like dentine, does not remodel and provides an archive of early geographic and dietary origins during its formation. Like dentine, enamel is laid down in incremental layers, beginning at the occlusal surface of the crown and ending at the enamel root junction (ERJ) (Suga et al., 1979; Suga, 1982).

Enamel is formed by ameloblasts in a two-stage process called amelogenesis. The first stage is the matrix production phase, where proteins, water and mineral form an organic matrix containing crystallites. The second stage involves removing the protein component and the water and enlarging the crystallites, creating a heavily mineralised mature enamel. Approximately 25% of hydroxyapatite is deposited at the time of initial formation, and the remaining 75% added subsequently in a process of enamel maturation (Passey and Cerling, 2002). The geometry of enamel maturation is complex, because waves of enamel mineralisation occur on different fronts and at different rates (Zazzo et al., 2005). In cattle, enamel maturation takes at least 6-7 months (Balasse, 2002). Despite significant time-averaging, serial samples of enamel record seasonal variations in diet and drinking water (Fricke and O'Neil, 1996; Balasse, 2002, 2003; Balasse et al., 2002, 2003, 2012; Gillis et al., 2013; Tornero et al., 2016b).

4.3 Stable light isotopes in nature

Many elements have different isotopes (atoms with the same number of protons and electrons, but different numbers of neutrons), which can therefore be distinguished by their mass. Most of these isotopes are stable, and therefore do not alter in abundance with time. Light isotopes undergo physical and chemical reactions more readily, as they require less energy to form or break bonds. Consequently, light isotopes are usually more abundant in the products of incomplete reactions, whereas heavier isotopes are more abundant in residual starting materials. If the mass difference between the isotope pair is relatively large in relation to atomic mass, this causes measurable variation (termed 'fractionation') in the ratio of the isotopes as elements progress through ecological and hydrological cycles.

Hydrogen, carbon, nitrogen and oxygen are the key elements in living organisms on earth. All have more than one isotope, so the ratio between them can be used to infer environmental processes and answer questions in the archaeological record. The most commonly used isotopes in archaeology are those of carbon, nitrogen, oxygen and strontium.

Because the shift in isotope ratios is extremely small, we use the 'delta' (δ) notation as shown below. Delta values are expressed in parts per thousand or 'per mille' (‰):

$$\delta(‰) = [\ (R\ sample)/(R\ standard)\ \text{-1}] \text{ X } 1000$$

Where R is the ratio of the heavy to the light isotope in the sample or in the standard.

$^{13}C/^{12}C$ ratios are reported relative to Vienna PeeDee Belemnite (VPDB). $^{18}O/^{16}O$ ratios may be reported relative to Vienna PeeDee Belemnite (VPDB) or Standard Mean Ocean Water (SMOW). This thesis uses VPDB. $^{15}N/^{14}N$ ratios are reported relative to atmospheric nitrogen (AIR).

A positive δ value indicates that the sample has a greater proportion of the heavy isotope than the standard, and vice versa.

4.3.1 Carbon

There are three naturally occurring isotopes of carbon in the biosphere, ^{12}C, ^{13}C (both stable isotopes) and ^{14}C (radioactive isotope). CO_2 in the atmosphere contains approximately 99% ^{12}C and 1% ^{13}C. ^{14}C exists in much smaller quantities. The greatest fractionation in the carbon cycle occurs during photosynthesis in plants. Plants are depleted in the heavy isotope (^{13}C) relative to atmospheric CO_2 (the raw material for photosynthesis). This discrimination against ^{13}C varies according to the photosynthetic pathway employed, i.e. the Calvin-Benson (C_3), Hatch-Slack (C_4) or Crassulacean Acid Metabolism (CAM) pathways. The resultant patterning in $^{13}C/^{12}C$ is passed on to consumers at higher trophic levels.

4.3.1.1 Carbon isotopes in plants

Most plants in temperate and high latitude regions photosynthesise using the C_3 pathway (Figure 4.2). These include all trees, temperate grasses and woody plants. The first step in C_3 photosynthesis is that CO_2 from the atmosphere (with a $\delta^{13}C$ value of approximately -8‰[7]) diffuses through the stomata into the air-filled spaces within the leaf (Figure 4.2)(Kohn and Cerling, 2002; Fry, 2006; Michener and Lajtha, 2008) leading to a fractionation of -4.4‰ due to the slower movement of $^{13}CO_2$ compared with $^{12}CO_2$ molecules. A second fractionation occurs because the carboxylating enzyme, ribulose bisphosphate carboxylase (RuBisCo) bonds more readily to the lighter isotope, resulting in a fractionation of 29‰. As shown in Figure 4.3, this results in mean $\delta^{13}C$ values for all C_3 photosynthesising plants of -28.77 ± 2.68‰ (n=3478) and C_4 photosynthesising plants of -12.90 ± 1.52‰ (n=137) (Cornwell et al., 2016). Farquhar et al. (1989) showed that the $\delta^{13}C$ compositions of C_3 plants can be expressed by the following equation:

$$\delta^{13}C_{C3\ plant} = \delta^{13}C_{CO2} - a - (b - a)\frac{p_i}{p_a}$$

where $\delta^{13}C_{CO2}$ is the carbon isotope composition of atmospheric CO_2, a is the carbon isotope fractionation occurring during the diffusion of CO_2 into the leaf (4.4‰) , b is the

[7] Note that this value is constantly changing due to ongoing combustion of fossil fuels, but a value of -8‰ is used for the purposes of this discussion, as in Kohn and Cerling (2002)

carbon isotope fractionation which occurs from Rubisco (29‰), and $\frac{p_i}{p_a}$ is the ratio of partial pressure of atmospheric CO_2 inside the leaf relative to atmospheric pCO_2 (Tipple and Pagani, 2007).

The $\delta^{13}C$ composition of C_4 plants can be expressed as:

$$\delta^{13}C_{C4\,plant} = \delta^{13}C_{CO2} - a - (b_4 + b\Phi - a)\frac{p_i}{p_a}$$

where symbols are the same as for the C_3 photosynthesis equation and additionally, b_4 is the fractionation associated with the carboxylation of PEP (-6‰) and Φ is the proportion of carbon fixed by PEP that leaks out of the bundle sheath cell (Farquhar et al., 1989; Tipple and Pagani, 2007). See Figure 4.2 for a schematic representation of these principles.

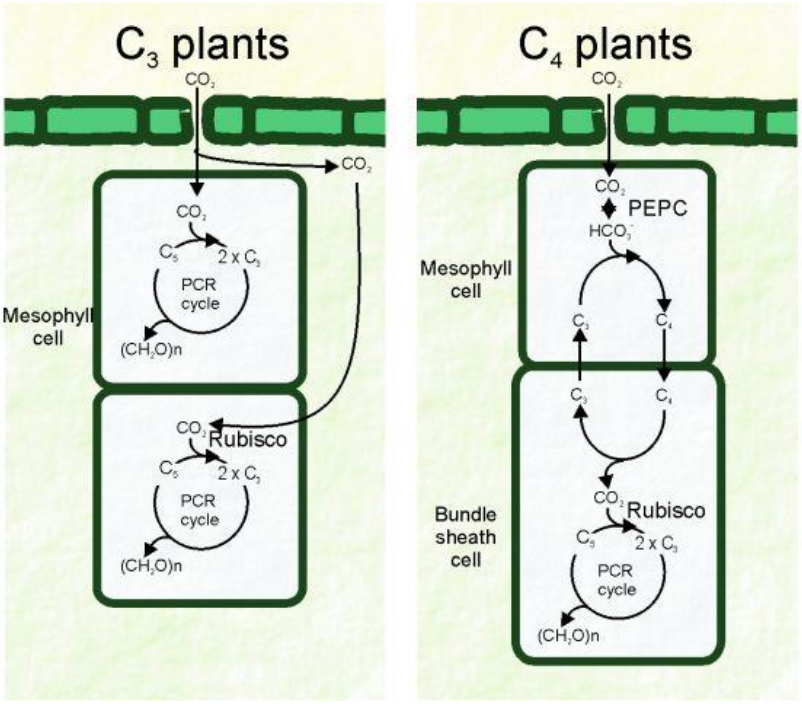


Figure 4.2: Differences in photosynthetic pathways for C_3 vs C_4 terrestrial plants, from Lara and Andreo (2011)

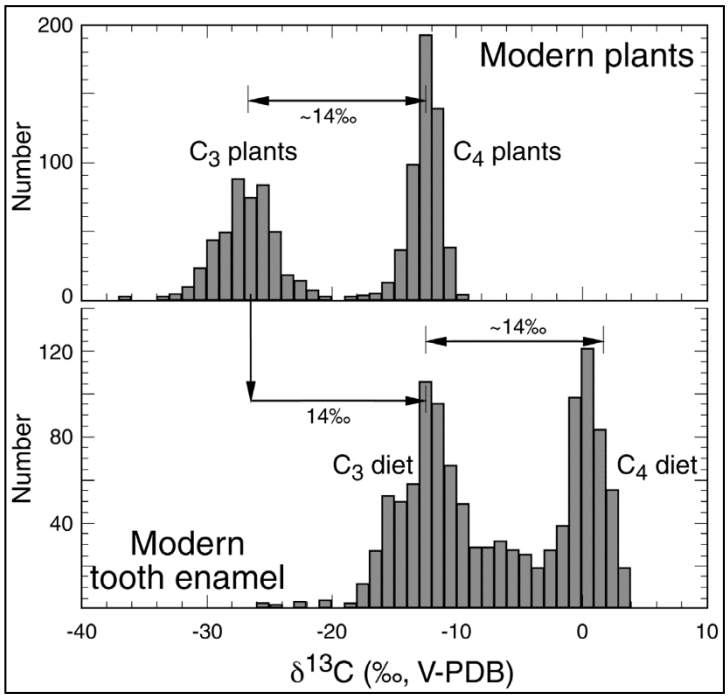


Figure 4.3: Distribution of $\delta^{13}C$ values in plants according to their photosynthetic pathway, and in tooth enamel of herbivore consumers (from Kohn and Cerling 2002)

C_4 photosynthesising plants consist mainly of grasses found in warmer, tropical to sub-tropical regions, but also occur in some temperate climates alongside C_3 plants. Economically important C_4 species include millets and sorghum, the key cultigens of pre-colonial sub-Saharan Africa. In C_4 photosynthesis, atmospheric CO_2 diffuses into the air-filled spaces inside the leaf, as in C_3 plants (Figure 4.2) (Fry, 2006; Michener and Lajtha, 2008; Lal and Baskaran, 2012). The same fractionation of around -4.4‰ occurs in this diffusion. Phosphoenol pyruvate (PEP) carboxylase enzyme catalyses the first stage of photosynthesis, combining with CO_2 to make a 4-carbon compound. This is transported into the bundle sheath cells (see Figure 4.2) where it is decarboxylated and the CO_2 released is reabsorbed and re-fixed by rubisco, with no loss of CO_2. PEP carboxylase has a much weaker preference for ^{12}C than rubisco, resulting in a fractionation of only about -6‰. This results in $\delta^{13}C$ values in the range of -9‰ to -16‰ for all C_4 photosynthesising plants (see Figure 4.3) (Cerling et al., 1997; Codron et al., 2005). Studies show that there is no overlap between the ranges of $\delta^{13}C$ values in C_3 and C_4 plants (Kohn and Cerling, 2002; Cornwell et al., 2016). More than 95% of all grasses in the summer rainfall regions of South Africa are C_4 grasses (Vogel et al., 1978).

Historically, at least three C_4 photosynthesising sub-types were suggested to exist based on the primary decarboxylating enzyme used: nicotinamide adenine dinucleotide-dependent

malic enzyme (NAD-ME), nicotinamide adenine dinucleotide phosphate-dependent malic enzyme (NADP-ME) and phosphoenolpyruvate carboxykinase (PCK) (Hatch, 1987). Recently however, multiple pieces of evidence have shown that no 'pure' PCK type exists, but rather NADP-ME and NAD-ME are distinct subtypes which can exist with or without the PCK pathway (Sage 2004, Wang et al., 2014; Rao and Dixon, 2016). Many crops and forage grasses belong to either NADP-ME (e.g. sugar cane *Saccharum spp*, sorghum *Sorghum bicolor*, maize *Zea mays*) or NAD-ME (e.g. switchgrass *Panicum virgatum*, pearl millet *Pennisetum glaucum*, amaranth *Amaranthaceae*).

Both C_4 sub-types undergo the initial carboxylation reaction catalysed by PEP carboxylase to yield the 4-carbon acid in the mesophyll cells. NAD-ME and NADP-ME differ in subsequent steps, namely in the site of decarboxylation, and in the transported metabolites (Ward et al., 1999; Sage 2004; Rao and Dixon, 2016). These differences have been shown to result in small differences in $\delta^{13}C$ values of different types of C_4 plants (Cousins et al., 2008; Cernusak et al., 2013) In NAD-ME grasses, the bundle sheath cells are more 'leaky' than in NADP-ME types, meaning that carbon dioxide is able to leak back into the mesophyll cells (Hattersley 1982). The more 'leaky' the bundle sheath cell, the more it will discriminate against ^{13}C and therefore result in a more negative $\delta^{13}C$ value of the plant. Differences of up to 2.9‰ have been reported between NAD-ME and NADP-ME plants, with values of PCK plants falling in between (Hattersley, 1982). NADP-ME plants are more abundant in moist environments and NAD-ME plants in dry environments (Cerling et al., 2013). In a study of plants with known C_4 sub-type, it was found that $\delta^{13}C$ values of NADP-ME plants in mesic environments ranged from -11.5 to -12.9‰ whilst $\delta^{13}C$ values of NAD-ME plants in xeric environments range from -12.1 to -14.4‰ (Cerling et al., 2003).

The vegetation in southern Zimbabwe has been outlined in section 2.2.3. Importantly, both sweetveld and sourveld grasses in the region mostly follow the NADP-ME pathway, except for *Eragrostis sp* which uses NAD-ME (Fish et al., 2015). It is therefore unlikely that $\delta^{13}C$ values of the grasses in sweetveld and sourveld can be distinguished based on C_4 sub-type. Variations in $\delta^{13}C$ of cattle teeth are therefore most likely to reflect variations in the amounts of C_3 plants (browse) consumed. Ethnographic records indicate that cattle are more likely to browse during dry periods, or in environments with inadequate graze.

CAM (Crassulacean Acid Metabolism) photosynthesis is an adaptation to water-stressed environments and mostly occurs in fleshy succulent plants. The photosynthetic pathway is

separated into night and day processes. During the night the plants' stomata are open, allowing CO_2 to enter the air-filled spaces where it is fixed by PEP carboxylase and stored as carbonic acids (Adams, 2010). During the day the stomata are closed (reducing evapotranspiration) and the acids are released and re-fixed by rubisco (Smith et al., 1976; West et al 2006). The $\delta^{13}C$ values of CAM plants depend on whether conditions favour C_3 or C_4 photosynthesis, and they can have values ranging across the spectrum of C_3 and C_4 plants. CAM plants are rare in southern Zimbabwe and are not favoured by cattle, so will not be discussed further.

Environmental factors have strong effects on the stable carbon isotope ratios in plants. There is a strong correlation between the $\delta^{13}C$ values of C_3 plants and rainfall (Swap et al., 2004; Murphy and Bowman, 2009; Diefendorf et al., 2010) with high $\delta^{13}C$ values (>-25‰) found in areas of low precipitation (Kohn, 2010). This pattern is seen on the global scale (Diefendorf et al., 2010). The relationship between $\delta^{13}C$ values of C_4 plants and precipitation is less clear, with one early study finding no correlation (Swap et al., 2004), although subsequent, more detailed studies have reported correlations (Murphy and Bowman, 2009; Lightfoot et al., 2020). While Murphy and Bowman (2009) reported the same pattern in C_3 and C_4 grasses (aridity leading to more positive $\delta^{13}C$), other studies have shown that $\delta^{13}C$ values in C_4 photosynthesizers become more negative under drought-stressed conditions (Cerling et al., 2003; Lightfoot et al., 2020).

Temperature considerably affects the $\delta^{13}C$ values in plants, especially temperature during the growing season. C_4 plants require more solar insolation to facilitate the extra step in photosynthesis. Therefore, C_4 grasses need a daily minimum above 8°C and maximum above 25°C to be more successful than C_3 grasses (Vogel et al., 1978; van der Merwe and Vogel 1983) The enzyme rubisco is less efficient in fixing CO_2 at high temperatures and therefore the yield of fixed carbon decreases with increasing temperature in C_3 plants (Ehleringer et al., 1997). In addition to this, C_4 plants can fix more CO_2 than C_3 plants at low CO_2 concentrations (Ehleringer et al., 1997). As a result of these different photosynthetic efficiencies at different temperatures, C_3 grasses dominate in winter rainfall (=cool growing season) areas, and C_4 grasses dominate in summer rainfall (=warm growing season) areas. The study region in southern Zimbabwe is within a summer rainfall zone. As in nearby areas of South Africa (Vogel et al., 1978), almost all grasses in this area follow the C_4 photosynthetic pathway.

Over the last couple of centuries, burning fossil fuels has had a major effect on both the amount of atmospheric carbon dioxide (pCO_2) and its isotopic ratios (Friedli et al. 1986; Marino and McElroy 1991). According to the Scripps Institute of Oceanography Global CO_2 programme (website accessed 5th August 2020), $\delta^{13}C$ of atmospheric CO_2 has declined by almost 2‰ compared with pre-industrial values. In order to compare modern tissues with those in the archaeological record, therefore, a correction factor needs to be applied. The size of this correction depends upon when the samples were collected. In this thesis, a value of 1.5‰ is used.

4.3.1.2 Carbon isotopes in animals

The $\delta^{13}C$ values of animal tissues reflect those of the food the animals consume, with some additional fractionation during digestion and tissue synthesis. Animals living in hotter and drier environments usually have higher $\delta^{13}C$ values, both because of the likely presence of C_4 grasses and because the $\delta^{13}C$ values of C_3 plants are more positive in these conditions (Diefendorf et al., 2010; Kohn, 2010). By measuring the $\delta^{13}C$ of herbivore tissues at archaeological sites, researchers can track the proportions of C_3 and C_4 plants back into the past.

Ungulates are frequently categorised into grazers which consume grass, browsers which consume the leaves of trees or shrubs and mixed feeders which consume both grass and trees/shrubs (Gagnon and Chew, 2000). In regions with C_4 grasses, we expect these broad consumer groups to show markedly different $\delta^{13}C$ values.

In animal tissues, carbon is derived from proteins, lipids and carbohydrates from diet. However, different tissues are synthesised from different 'pools' of dietary carbon and therefore do not reflect the same components of diet (Ambrose and Norr, 1993; Tieszen and Fagre, 1993). As outlined in the previous section, protein tissues such as bone and dentine are synthesised mainly from dietary amino acids, to the extent that these are available, but there is also some contribution of carbon from lipids and carbohydrates (Howland et al., 2003). Carbonate in bone and enamel apatite is synthesised from bicarbonates in blood plasma which derive more equally from proteins, lipids and carbohydrates (Ambrose and Norr, 1993; Tieszen and Fagre, 1993; Howland et al., 2003). Therefore diet-tissue fractionations differ. In large ruminants, fractionations are around +3 to +5‰ for collagen. For carbonates, values range from +11 in bone carbonate to +14‰

in tooth enamel(see Figure 4.4) (Passey et al., 2005; Warinner and Tuross, 2009; Schoeninger, 2014) .

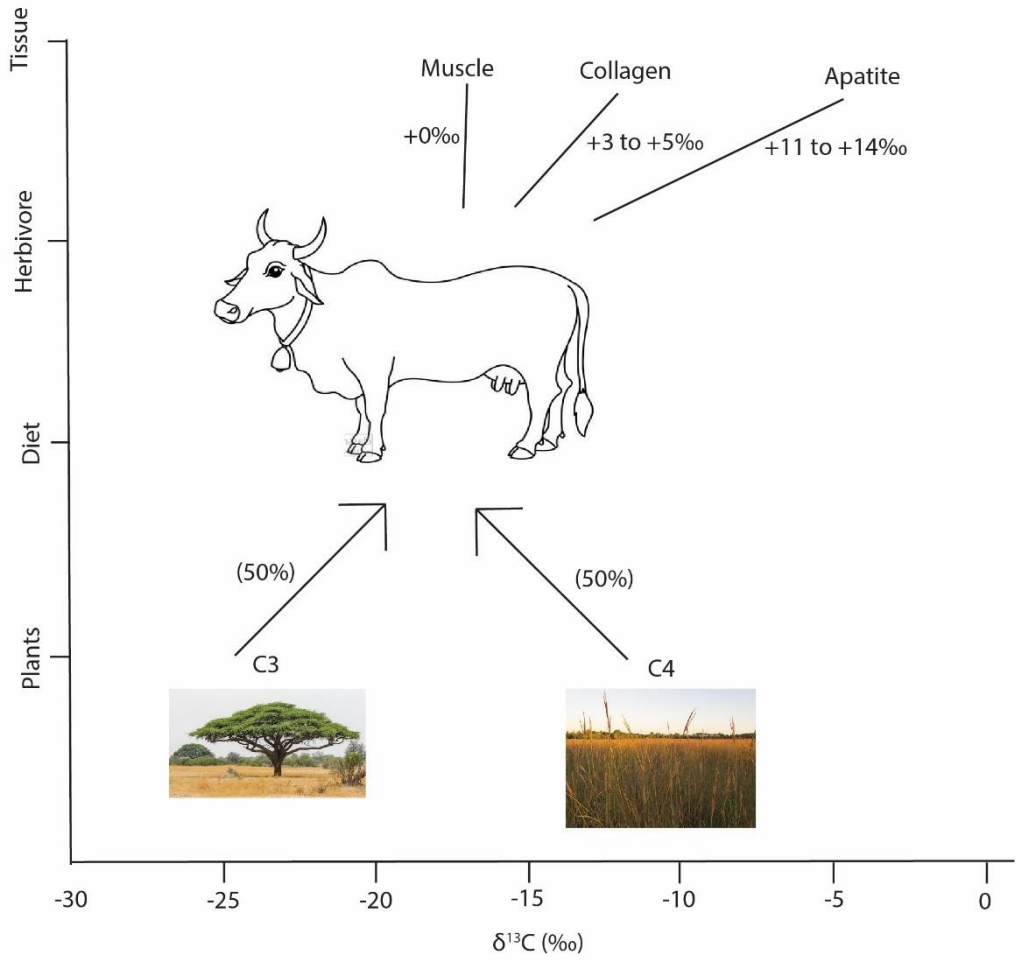


Figure 4.4 Diet to tissue fractionation for stable carbon isotopes in large mammals

If there is a 14‰ difference between a 100% C_3 diet and a 100% C_4 diet (Kohn and Cerling, 2002) in animal tissues, then one can estimate the percentage change in diet. A 1‰ shift in the $\delta^{13}C$ value of animal tissues equates to approximately a 7% change in diet ([1‰ ÷ 14‰] ×100 = 7%). These are only estimates however, as end-values for 100% C_3 and C_4 diets can vary by a few per-mille. These estimates can be used where mixing models to calculate end-members of diet are not necessary.

In an isotopically homogeneous diet, the relationship between $\delta^{13}C_{collagen}$ and $\delta^{13}C_{carbonate}$ is expected to be linear (R^2 =1). The difference between $\delta^{13}C_{collagen}$ and $\delta^{13}C_{carbonate}$ can be expressed loosely (by simple subtraction) as $\Delta^{13}C_{collagen\text{-}carbonate}$ or more rigorously as $\varepsilon^*_{collagen\text{-}carbonate} = 1000[\alpha_{collagen\text{-}carbonate} - 1]$ where $\alpha_{collagen\text{-}carbonate} = ([1000 +$

$\delta^{13}C_{collagen}]/[1000 + \delta^{13}C_{carbonate}])$. ε values are mathematically correct, because they consider that δ values are ratios.

Variability in $\Delta^{13}C_{collagen\text{-}carbonate}$ is itself a dietary indicator, with smaller values in lipid-rich (typically carnivorous) diets and higher values in herbivorous diets (Krueger and Sullivan, 1984; Lee-Thorp et al., 1989; O'Connell and Hedges, 2017; Codron et al., 2018). Previous studies of apatite-collagen spacing have been limited by the difficulty of distinguishing patterns/relationships resulting from qualitative differences in the diets of herbivores and carnivores, from patterns/relationships driven by differences in herbivore/carnivore digestive physiology.

Physiological effects also play a role. In some herbivores, including cattle, microbial activity in the gut during digestion results in production of highly ^{13}C depleted methane (CH_4), which is then eliminated. This leaves blood plasma enriched in ^{13}C, leading to more positive $\delta^{13}C_{carbonate}$ (Hedges, 2003; Passey et al., 2005). Respired CO_2 is depleted in ^{13}C. Some CO_2 is resorbed into blood plasma, increasing the $\delta^{13}C$ values of the blood bicarbonate from which apatite is synthesised (Hedges, 2003; Passey et al., 2005). The offset between diet and tooth enamel is +14‰ for animals that rely on extensive microbial fermentation in their guts, and +10‰ for those that don't (Passey et al., 2005; Kellner and Schoeninger, 2007).

4.3.2 Nitrogen

Dinitrogen gas (N_2) makes up 78% of the earth's atmosphere. Atmospheric nitrogen contains approximately 99.6% ^{14}N and 0.4% ^{15}N. Atmospheric nitrogen is a well-mixed reservoir with a $\delta^{15}N$ value of 0‰ (by definition, since it is the standard).

4.3.2.1 Nitrogen isotopes in plants

The N_2 molecule contains a triple bond, making it stable and relatively difficult to convert into other nitrogen-containing molecules. Plants cannot use N_2 directly, although some (e.g. legumes) have nitrogen-fixing bacteria on their root nodules. These "nitrogen-fixing" plants may have very variable $\delta^{15}N$ values of between -10 ‰ and +10 ‰ (Peterson and Fry, 1987). Most plants do not fix nitrogen, so rely on soil bacteria to convert N_2 into a

usable form such as NH_4^+ or NO_3 (Robinson, 2001). Many inter-conversions between NH_4, NO_2 and NO_3 occur in soils, each associated with different degrees of fractionation of the N isotopes. Source of nitrogen (whether a plant takes up nitrogen in the form of NH_4 or NO_3) is a major determinant of plant $\delta^{15}N$ (Szpak, 2014).

Nitrogen assimilation generally occurs in the roots, and nitrogen-containing compounds are allocated to the various parts of the plant, resulting in different $\delta^{15}N$ values in different plant parts. Plant $\delta^{15}N$ also depends on rooting depth (Amundson et al., 2003; Hobbie and Högberg, 2012), following increasing soil $\delta^{15}N$ with depth. The extent of this depends on precipitation, drainage and N_2 content of the soil (Evans and Ehleringer, 1994).

Some plants benefit from mycorrhizal activity. Mycorrhizal fungi contain large areas of mycelium, which absorb nutrients from a large volume of soil and provide some to the plant (Joseph et al., 2009). Fixed nitrogen (NH_4, NO_3 etc) provided in this way is generally depleted in ^{15}N. Thus, plants with associated mycorrhizae have lower $\delta^{15}N$ values than those without (Szpak, 2014).

Globally, $\delta^{15}N$ values of plants correlate negatively with rainfall (Heaton, 1987; Handley et al., 1999; Hedges et al., 2004). This is largely as a result of denitrification: the process whereby fixed nitrogen is converted back into gaseous N_2. This process is associated with stronger fractionation than nitrogen fixation: ^{14}N is preferentially converted into N_2 leaving the soil enriched in ^{15}N. This tends to occur to a greater extent (the nitrogen cycle is more 'open') in arid environments, so that plant $\delta^{15}N$ values in arid environments are high (Handley et al., 1999; Craine et al., 2009).

Murphy and Bowman (2009) found a similarly strong (R^2=0.42) negative correlation between rainfall and plant $\delta^{15}N$ for plants using C_3 and C_4 photosynthetic pathways. In a southern African context, Swap et al. (2004) found a much stronger correlation between rainfall and $\delta^{15}N$ of C_3 plants (R^2=0.54) than C_4 plants (R^2=0.04). Codron et al., (2013) found no correlation with either C_3 or C_4 plants. However, this may have been because the range of rainfall in the area of study (Kruger National Park, South Africa) was too small to show this pattern.

Soil substrates may also influence $\delta^{15}N$ values of plants. One study showed that $\delta^{15}N$ values of plants collected from dry, sandy soils are higher than those collected over clay-based basalt-derived soils (Heaton, 1987). However, this was found not to be the case in a more recent study of the Kruger National Park in South Africa, where $\delta^{15}N$ values of plants

derived from clayey loams were higher than those from sandy soils (Codron et al., 2005). In fact, the highest values were found to be in plants derived from saline environments (Heaton, 1987; Codron et al., 2005). Salinity is one type of water limitation, so saline environments can be compared in some respects to very arid ones.

Animal fertilizers have been used to increase soil fertility for crop production over millennia (Jones, 2012). Crops grown in soil manured over several years may have $\delta^{15}N$ values up to 10‰ higher than those which have not been manured (Bol et al., 2005; Fraser et al., 2011; Bogaard et al., 2013). Pig manure can raise plant $\delta^{15}N$ by a factor of two compared with cattle manure (Szpak, 2014), because 75-90% of the nitrogen in pig manure is available to plants over a period of one year, compared with only 20-40% for cattle manure. This may be relevant to this study because if cattle were let into agricultural fields after the harvest (during dry seasons) to feed on crop residues, leading to incidental manuring of the fields, this might lead to elevated $\delta^{15}N$. Evidence for this practice amongst contemporary farmers was outlined in Chapter 3.3.2.

4.3.2.2 Nitrogen isotopes in animals

$\delta^{15}N$ values of consumer tissues reflect the protein component of diet (Koch, 2007). Animals are enriched in ^{15}N compared with their diets (Schoeninger and DeNiro, 1984; Sponheimer et al., 2003; Codron et al., 2007a; O'Connell et al., 2012). This increase (diet-tissue fractionation) has been estimated as +3 to +6‰ (Figure 4.5) (Bocherens and Drucker, 2003; O'Connell et al., 2012).

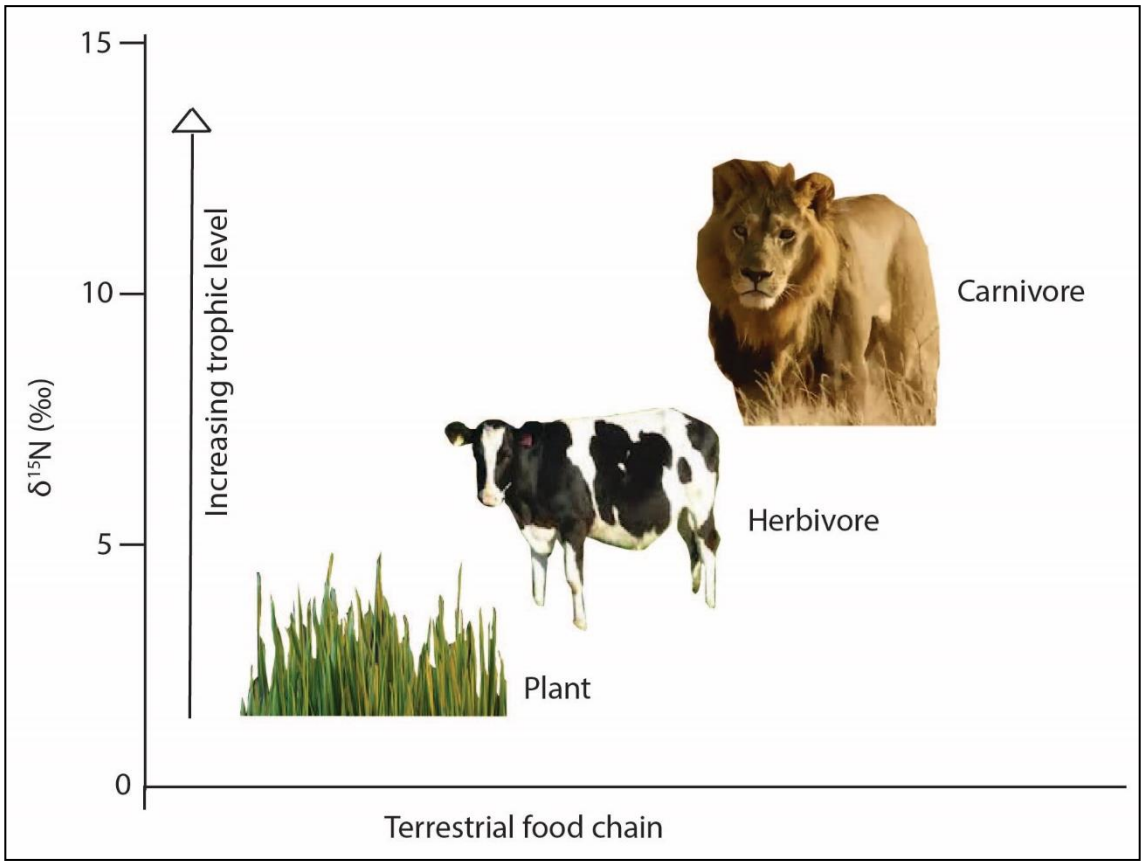


Figure 4.5: Shifts in $\delta^{15}N$ values with increase in trophic level [adapted from Schulting (1998)**]**

There may be differences in the trophic level enrichment factor at different trophic levels but because this study is limited to cattle, this review will focus on sources of variation in herbivores. Animals in dry areas tend to have higher $\delta^{15}N$ values (Grocke et al., 1997; Schulze et al., 1998; Kelly, 2000; Richards and Hedges, 2003). Some authorities argue that this results entirely from higher $\delta^{15}N$ of foods consumed. The pattern of $\delta^{15}N$ in kangaroo bone collagen from different environments across Australia mirrored that of plant $\delta^{15}N$, leading the authors to conclude that variation in $\delta^{15}N$ of animals derives directly from the diet, rather than metabolic processes within the animals (Murphy and Bowman, 2006). However, this study was based only on one genus. Different herbivore species eating the same diet can show differences in $\delta^{15}N$ of up to 3.6‰, indicating that metabolic processes can play a role (Sponheimer et al., 2003).

Sponheimer et al. (2003) have also shown that $\Delta^{15}N_{consumer\text{-}diet}$ can increase by 2.3‰ in high- compared with low-protein diets. This probably contributes to $\delta^{15}N$ values of browsers tending to be more positive than those of grazers (Ambrose, 1991; Evans and Ehleringer, 1994; Codron et al., 2007b; Robbins et al., 2010). Particularly in dry seasons,

grasses usually contain less protein than trees and shrubs. Grasses also tend to be shallow-rooted plants, obtaining their nitrogen from the upper part of the soil profile where $\delta^{15}N$ is lower. Browse foods such as trees and shrubs contain higher protein content but also contain tannins and secondary chemicals making them more difficult to digest (Codron et al., 2007c).

Some studies have proposed that metabolic processes play a role in $\delta^{15}N$ values of animal tissues. Microbial activity in the gut may contribute to raised $\delta^{15}N$ in body tissues (Sealy et al., 1987). Urea recycling in drought-tolerant animals leads to the excretion of highly ^{15}N-depleted urea, and enrichment of body tissues in ^{15}N (Ambrose, 1991), but if the loss of N in faeces is also taken into account, the overall effect may be reduced (Sponheimer et al., 2003). There is clearly considerable complexity here, making interpretation of $\delta^{15}N$ in consumer tissues difficult.

The age at which juvenile animals were weaned can be identified by tracking changes in $\delta^{15}N$ values in early-forming teeth. This principle was first established in humans (Fogel et al., 1989; Katzenberg et al., 2002) and later applied to domestic animals (Balasse et al., 2001; Balasse, 2002). Because $\delta^{15}N$ values shed light on the trophic level of the animals, and a suckling animal is a higher trophic level than its mother, the lowering of the $\delta^{15}N$ value of the suckling animal to the same level as its mother usually indicates the process of weaning. Establishing weaning age in domesticated animals such as cattle enables one to assess whether ancient herds were managed to maximise milk production, or with other goals in mind.

4.3.3 Oxygen

Oxygen has three stable isotopes: ^{18}O, ^{17}O and ^{16}O. ^{16}O is the most abundant stable isotope (99.8%) with ^{18}O and ^{17}O being less so (0.2% and 0.0375% respectively). This study reports $^{18}O/^{16}O$ as $\delta^{18}O$ values relative to VPDB. Oxygen in the biosphere occurs as molecular oxygen (O_2) and in organic and inorganic molecules, but much of the patterning in $^{18}O/^{16}O$ in plants and animals is determined by water.

$\delta^{18}O$ in precipitation is dependent on several factors:

1) The latitude effect: rainwater has more negative $\delta^{18}O$ as latitude increases (and temperature decreases).

2) Elevation effect: more negative $\delta^{18}O$ with increasing altitude.
3) Continental effect: more negative $\delta^{18}O$ as the air mass moves inland.
4) Seasonal effect: More negative $\delta^{18}O$ in winter, less negative $\delta^{18}O$ in summer.
5) Amount effect: More negative $\delta^{18}O$ when more precipitation falls ($H_2{}^{18}O$ raindrops fall first)

Of these, the seasonal and elevation effects are the most relevant to this study.

4.3.3.1 Oxygen isotopes in plants

Oxygen isotopes are mostly incorporated into the plant from water, with some entering because molecular oxygen dissolves in leaf moisture and is then absorbed. Therefore, plant water $\delta^{18}O$ depends on the $\delta^{18}O$ of the water source (Barbour, 2007). During the uptake of water by plants there is little to no fractionation during the movement of water into the plant's roots, or during the flow of water through the xylem (Dawson and Ehleringer, 1993). Leaf water is, however, enriched in the heavy isotope due to $H_2{}^{16}O$ transpiring more readily than $H_2{}^{18}O$. Thus, variation in plant $\delta^{18}O$ is mainly the result of precipitation inputs and evaporation of leaf water during transpiration, both of which are influenced by relative humidity and temperature. At high temperatures, there will be more transpiration leading to higher plant $\delta^{18}O$ values. If there is high relative humidity, plant $\delta^{18}O$ values will be lower. Accordingly, stable oxygen isotopes in plant and animal tissues can be used as a proxy for climate change.

4.3.3.2 Oxygen isotopes in animals

Oxygen is incorporated into the body through drinking water, inspired O_2 and oxygen in food. Oxygen is released from the body through sweating, panting and respired CO_2, and in urine and faeces [Figure 4.6 adapted from Lee-Thorp (2002)]. Liquid water lost from the body is usually in isotopic equilibrium with body water, but water vapour lost from the body is depleted in ^{18}O as ^{16}O is released preferentially (Wong et al., 1988). Therefore, the physiological adaptations by mammals to heat stress are significant when interpreting $\delta^{18}O$ values. For example, if two species have isotopically equal inputs, a species which cools

by panting will have higher $\delta^{18}O$ than one which cools by sweating (Sponheimer and Lee-Thorp, 2001).

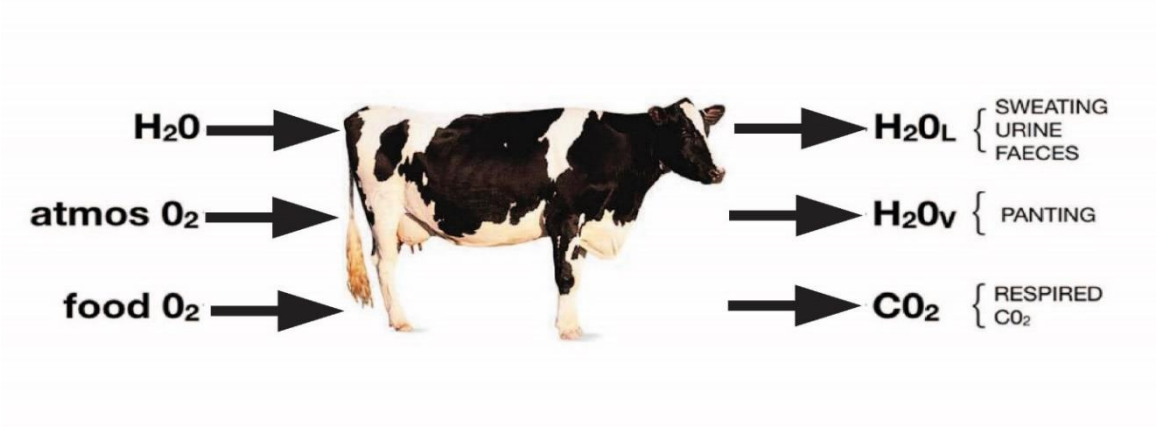


Figure 4.6 adapted from Lee-Thorp (2002)

In early years, research into stable oxygen isotopes focussed on phosphate (as opposed to carbonate) compounds in bone and teeth. This is because the very strong P-O bond was thought to be resistant to post-depositional chemical alteration (Luz et al., 1984). Ayliffe et al., (Ayliffe et al., 1994) subsequently showed diagenesis in $\delta^{18}O_{phosphate}$ of Plio-Pleistocene fossil bone/dentine, though not tooth enamel. In recent years, confidence in our ability to recover biogenic signals from carbonate has increased. In the 1980s the dominant view was that carbonate was too unstable to maintain its original isotopic composition over archaeological timescales. Lee-Thorp and van der Merwe (1987) demonstrated that C_3 browsing and C_4 grazing signals were maintained in the fossil record in bone carbonate. If carbon isotopes maintained their original composition, then oxygen isotopes would be likely to have done so too. From the 1990s most research based on $\delta^{18}O$ shifted to carbonate tissues. Analysis of enamel is preferred as the more open, porous structure of bone facilitates diagenesis while the denser, more crystalline structure of enamel does not. Measuring $\delta^{18}O_{carbonate}$ has become the preferred approach for two reasons: first, carbonates offer the opportunity to analyse carbon isotopes and oxygen isotopes simultaneously, and second, the pre-treatment methods for carbonates are less time consuming than those for phosphate, allowing multiple samples to be analysed more rapidly (Lee-Thorp, 2002). This study reports analyses of $\delta^{18}O_{carbonate}$ and therefore phosphate will not be discussed further.

Leaf water is enriched in ^{18}O relative to groundwater due to evapotranspiration (Yakir, 1992), although stem water is not. Thus, $\delta^{18}O$ values of browsing animals (especially those that obtain much of their water from their food) tend to be higher than those of grazers

(which typically obtain most of their water by drinking). Further, browsing species which feed selectively on leaves tend to have higher $\delta^{18}O$ values than those which bulk feed on stems and leaves, as stems have lower $\delta^{18}O$ than leaves (Kohn, 1996; Cerling et al., 1997; Sponheimer and Lee-Thorp, 1999, 2001). Levin et al., (2006) used $\delta^{18}O_{carbonate}$ in tooth enamel to develop a proxy for aridity. They compared animals that obtained much of their water from their food ('evaporation-sensitive' species) with those that obtained their water by drinking ('evaporation-insensitive' species). The offset between $\delta^{18}O_{meteoric\ water}$ and $\delta^{18}O_{enamel}$ increased in proportion to aridity in evaporation-sensitive species.

Cattle are obligate drinkers, obtaining most of their water requirements from drinking water. We therefore expect that their $\delta^{18}O$ values will track their drinking water, rather than their food. Even amongst obligate drinkers, species that drink more frequently tend to have lower $\delta^{18}O$ values (Sponheimer and Lee-Thorp, 2001) and non-obligate drinking herbivores in arid and semi-arid areas tend to have higher $\delta^{18}O$ (Levin et al., 2006; Blumenthal et al., 2017) . $\delta^{18}O$ of obligate drinkers tracks drinking water from lakes, streams, wells and leaf water (Dansgaard, 1964; Kohn et al , 1996). Animals that drink from lakes and larger water bodies, are usually more isotopically stable through changing seasons. Those that drink from rivers will have more variable stable oxygen isotope values through the seasons, tracking variation in precipitation (Pederzani and Britton, 2019). Ground water (for example, well water) also closely tracks precipitation $\delta^{18}O$ values (Bowen et al., 2011). There are no natural lakes around Great Zimbabwe, and it is therefore likely that cattle drank from perennial streams and possibly wells in the dry season. $\delta^{18}O$ values of cattle teeth from this area are therefore expected to track precipitation without major alteration by surface evaporation.

4.3.4 Strontium

There are four naturally-occurring strontium isotopes: ^{84}Sr, ^{86}Sr, ^{87}Sr and ^{88}Sr with natural abundances of 0.56%, 9.87%, 7.04% and 82.53% respectively. All four are stable isotopes. ^{87}Sr is the only radiogenic isotope and forms as a result of the decay of ^{87}Rb, which has a half-life of approximately 4.88×10^{10} years. $^{87}Sr/^{86}Sr$ is therefore higher in rocks with high rubidium contents and in older geological formations (Faure, 1977).

The mass difference between ^{87}Sr and ^{86}Sr is very small (~1%), therefore very little fractionation occurs between the weathering of rocks and the uptake of strontium isotopes

into plants and animals. This makes the strontium isotope ratios in living organisms very similar to those of the underlying geology (Hurst and Davis, 1981; Sillen et al., 1998; Montgomery et al., 2000). However, the various constituent minerals contained within rocks can weather at different rates, leading to different $^{87}Sr/^{86}Sr$ ratios released into the biological system (Sillen et al., 1998; Price et al., 2002). Rivers, streams and dust storms can introduce non-local strontium-containing materials, altering the biologically available $^{87}Sr/^{86}Sr$.

Chemical similarity leads to Sr^{2+} substituting for Ca^{2+} in plant and animal tissues. Sr^{2+} is included into the apatite structure because it is similar in size and has the same charge as Ca^{2+}; controlling mechanisms filter out some of the Sr^{2+}, but not all.

$^{87}Sr/^{86}Sr$ in herbivores therefore reflects that of the bedrock over which that animal roamed and fed, and can be used to reconstruct movements across different geological zones, if these have contrasting $^{87}Sr/^{86}Sr$ (Ericson, 1985; Price et al., 1994; Sealy et al., 1991; Montgomery et al., 2000; Montgomery, 2010; Evans et al., 2012). To do this, the range of biologically available $^{87}Sr/^{86}Sr$ needs to be established for each rock type of an area. Sillen et al. (1998) measured $^{87}Sr/^{86}Sr$ in plants, water, soil and bedrock around Swartkrans in the Sterkfontein valley in South Africa. Soil values were extremely variable, while bioavailable values as reflected in plants were less so. Streams and rivers may carry 'foreign' strontium from farther upstream, leading to altered $^{87}Sr/^{86}Sr$ in riparian vegetation. Studies that use $^{87}Sr/^{86}Sr$ as a tracer generally monitor bioavailable values by measuring plants and animals (rather than soils) as these average out small-scale local variations. Plants are frequently the easiest samples to obtain to establish environmental baselines. In their large study of bioavailable $^{87}Sr/^{86}Sr$ in southernmost Africa, Copeland et al., (2016) collected a handful of plant material from each of five different plants at each collection point, and combined them into a single sample before analysis.

Researchers have taken different approaches to estimating 'local' $^{87}Sr/^{86}Sr$ based on measurements of suites of environmental samples. Some researchers (Sealy et al., 1995; Cox and Sealy, 1997; Sillen et al., 1998; Bentley et al., 2002; Bentley, 2006; Vaiglova et al., 2018; Isaakidou et al., 2019) use the full range of $^{87}Sr/^{86}Sr$ variation found in their sets of environmental samples to define 'local'. Others take the mean ± 2 standard deviations, arguing that excluding outliers is a better way to objectively identify the local range (Price et al., 2002; Bentley et al., 2004; Price et al., 2006; Price et al., 2007; Price et al., 2008; Price et al., 2010). This of course pre-supposes large sample sizes. However, in establishing

the range of 'local' $^{87}Sr/^{86}Sr$ it is important not to under-estimate the amount of variation within one bedrock geology. As such, this study will take the entire range of $^{87}Sr/^{86}Sr$ found on each geological substrate to establish 'local' values.

4.4 Assessing diet, animal movement and environment using stable isotopes

A whole range of applications using stable isotopes as dietary and environmental tracers has been published since the first, pioneering work in life sciences (Vogel and van der Merwe, 1977; DeNiro and Epstein, 1978; van der Merwe and Vogel, 1978). Research into the movement of animals, humans, traded goods and food has become a major focus in archaeological research (e.g Dupras and Schwarcz, 2001; Balasse et al., 2002; Hedges et al., 2005; Price et al., 2006; Bentley, 2007; Meiggs, 2007; Barrett et al., 2008; Britton et al., 2009). These kinds of research questions are key to understanding resource acquisition strategies, the extent of social networks and defining political boundaries of past human populations (Meiggs, 2007; Guiry et al., 2012).

Inferring animal husbandry practices in the past is vital to gain an understanding of the economic structure of prehistoric societies. Key insights include production goals (i.e. wool, meat, milk), and grazing and foddering strategies. Strontium isotope analysis of tooth enamel allows for the detection of animal movement across the landscape (Balasse et al., 2001; Balter, 2008; Viner et al., 2010; Evans et al., 2012; Arnold et al., 2013). This can inform us about dietary and resource exploitation strategies (Balasse et al., 2002; Makarewicz and Tuross, 2009, 2012; Smith et al., 2010; Tornero et al., 2016b), and can be even more powerful when used in combination with stable isotope analyses of the same specimens.

Climatic and environmental reconstructions are essential in understanding the dynamics associated with the duration of occupations of archaeological sites, advancements in human technologies and in more recent times, the rise and fall of complex state systems. Stable isotope analyses have proven useful in combination with archaeological material evidence, to build models for these factors. In southern Africa, the materials most often studied using stable isotopes for environmental reconstruction are stalagmites (Holmgren et al., 1999, 2003; Bar-Matthews et al., 2010), charcoal residues, lake cores, wood remains (Woodborne et al., 2008, 2015; Hall et al., 2008) and fauna (Lee-Thorp and Sponheimer, 2003; Smith, 2005; Luyt, 2012; Roberts et al., 2016; Luyt et al., 2019).

4.4.1 Serial sampling tooth enamel and dentine

Recently, a major goal in stable isotopic studies has been to achieve more detailed and higher resolution records. One way to do this is through serial sampling of tissues that grow incrementally and do not remodel. In archaeological faunal remains, the most suitable tissue for these purposes is tooth dentine and enamel.

Pioneering work on serial sampling of teeth aimed to establish their chronological integrity during their formation. The best way to do this was to conduct controlled feeding studies on domesticates and measure the stable isotope ratios of their teeth. The ground-breaking work of Balasse et al. (2001) serially sampled cattle teeth to find out whether a dietary shift from C_3 to C_4 food was reflected in $\delta^{13}C_{\text{dentine collagen}}$. The inclusion of C_4 grasses appeared to be reflected in the teeth earlier than the C_4 diet had begun. They hypothesised that this resulted from the cone-shaped pattern of dentine deposition resulting in a time averaging effect in the sub-samples. Although serial sampling of dentine captured the C_3/C_4 diet switch, it did not reflect the rapidity of the switch. A more time-sensitive sampling strategy confirmed the observations of Balasse et al. (2001) by comparing high resolution longitudinal and transverse serial samples of dentine from the same animals (Zazzo et al., 2006). The results of this study showed that in cattle, time averaging for transverse profiles is four months, whereas in longitudinal samples, time averaging was estimated to be 8-9 months (Zazzo et al., 2006). These authors also found that sampling the innermost layer of dentine provided the least dampened isotopic signal of a diet-switch, but the small size of the narrow zone made this difficult.

In archaeological remains, enamel carbonate is less susceptible to diagenesis than dentine collagen and therefore is the preferred tissue for stable isotope analyses in deep time (Lee-Thorp and van der Merwe, 1987; Bocherens et al., 1996). Tooth enamel, however, develops over a period of several months and so the time of initial enamel formation is not the same as the time of the final deposition of mineral. At the time of initial formation, enamel contains 25% (by volume) of the mineral with the remaining 75% (by volume) accumulating during the maturation process (Passey and Cerling, 2002). This leaves each serial sub-sample producing a time-averaged isotopic signal over the maturation period. A feeding study in cattle and sheep showed that the time taken for enamel maturation in these species was six to seven months (for second molars) and this delay should be considered

when interpreting seasonality (Balasse, 2002; Zazzo et al., 2010). Another study showed that different layers of enamel mineralise at different rates, and suggested that the inner and middle layers of enamel should be sampled instead of the outer layer, as the outer layer mineralised more slowly (Trayler and Kohn, 2017). One further complication in serially sampled teeth is that different parts of a tooth may capture environmental variations differently. Feeding studies showed that in sheep, the mesial side of the M3 showed a larger intra-tooth variation than the buccal side (Zazzo et al., 2012).

For this study, the most important research questions to be explored using stable isotope analyses of serial samples of teeth are mobility, diet and foddering practices and seasonality of birth and weaning. A review of previous research on these topics is provided below.

4.4.1.1 Mobility

Carbon, oxygen and strontium isotopes can be used to track animal movement (e.g. Balasse et al., 2002; Henton et al., 2010; Viner et al., 2010; Sjögren and Price, 2013; Arnold et al., 2013; Valenzuela-Lamas et al., 2016; Tornero et al., 2016a; Vaiglova et al., 2018; Isaakidou et al., 2019; Shulting et al., 2019). Serially sampled tooth enamel tracks animal movement over periods of one year or two, depending on the length of time a tooth takes to grow. One can get a longer chronological record by sampling several teeth from the same animal (e.g. M1, M2 and M3)

One frequently used comparison is between herd mobility in the past and ethnographic records collected in the present. On the south-west coast of southern Africa, Balasse et al., (2002) tested a hypothesis of seasonal movement by pre-colonial herders, based on the times of year at which 15^{th}-17^{th} century ships encountered indigenous peoples with and without domesticated animals along the coast. Stable carbon and strontium isotope analyses of serial samples of sheep tooth enamel did not show a clear pattern of mobility between the coast and the interior. The movement hypothesised on the basis of the historical record may have been a more recent development. A similar incongruence between ethnographic evidence and archaeological mobility patterns (reconstructed from stable isotopes) was found for East African pastoralists (Janzen, 2015).

Identifying herd mobility strategies can shed light on subsistence specialisation and how these affected the growth and decline of complex states of the past. For many years,

specialisation has been thought to be a key ingredient in developing complex state systems (see McIntosh, 1999). Within farming communities, transhumance strategies are considered to indicate a level of specialisation. This is because it requires time and energy and specialised knowledge to optimise seasonal movement of herds around the landscape. Serially sampled tooth enamel of cattle from Jenne-Jeno in West Africa, however, showed that these herds were not solely the product of specialized transhumant pastoralism (Stone, 2018). Modern-day herders, on the other hand, did use transhumant strategies (Stone, 2018). The implication of this study is that subsistence specialisation may not have been as important in developing complex West African states as archaeologists had hypothesised.

In contrast, this level of specialisation is evident in the Shashe-Limpopo Basin: the suggested origins of political specialisation in southern Africa. Fauna recovered from state capitals such as K2 and Mapungubwe showed that transhumance strategies, assuming subsistence specialisation, were used in this arid environment to maximise nutrient intake for the herds and to limit over-grazing (see McIntosh 1999; Smith et al., 2010). The use of different grazing areas shows an in-depth knowledge of pasture management and an investment of time and energy into moving the herds seasonally. This work identified a response in herd management strategies to the declining environmental conditions experienced in the region at the decline of Mapungubwe as a state-level capital. In this case, as the population increased, the environment declined and the political landscape changed, domestic herds were moved away from the Shashe-Limpopo Basin and only brought in for slaughter or tribute. The implication is that herd management strategies were fluid and reacted to changing environmental conditions and political expansion in the region.

These questions were also targeted at Early Iron Age sites in KwaZulu-Natal of southern Africa where $^{87}Sr/^{86}Sr$ of serial samples of cattle tooth enamel were used to investigate possible herd movement (Arnold et al., 2013). The authors found that even though modern-day herders were using transhumant strategies, they were unable to identify this pattern in Iron Age remains. Unfortunately, the authors had difficulty in monitoring the biologically available strontium isotope variation on a large enough scale, limiting their ability to draw firm conclusions.

4.4.1.2 Diet and Foddering

Foddering in the archaeological record is usually identified by $\delta^{13}C$ and/or $\delta^{15}N$ values in domesticated animal tissues, reflecting diets to which the animals would not have had access in the natural environment. The inference is human provision of food (Makarewicz and Tuross, 2006, 2009; Makarewicz, 2014; Makarewicz 2017; Makarewicz and Pederzani, 2017).

Ethnographic accounts of foddering provide a source of hypotheses that can be tested in the archaeological record using stable isotopes (Halstead, 1998; Makarewicz and Tuross, 2006; Chakeredza et al., 2007). For example, Makarewicz and Tuross (2006) used $\delta^{15}N$ and $\delta^{13}C$ in dentine to show significant differences in diet between provisioned and non-provisioned caprines. Humans were providing C_4 plants to the domesticates, so they consumed ^{13}C-enriched foods all year round, whereas wild caprines were consuming C_3 plants in the dry months. In Asia, C_4 dicots are more common than they are in the rest of the world. In this study, the most important C_4 plant was the shrub *Salsola*. They also found higher $\delta^{15}N$ values in provisioned domesticates and attributed this to either improved nutrition (by extended lactation) or to the fodder having relatively high $\delta^{15}N$ values.

Other studies have identified winter leaf foddering in tooth enamel where low $\delta^{13}C$ values (indicating C_3 consumption) coincide with low $\delta^{18}O$ values (indicating cool, winter months) in the European Neolithic (Balasse et al., 2013). In this case, the animals remained close to the site and winter leaf foddering was a response to adverse environmental conditions.

4.4.1.3 Seasonality: birth and weaning

Domesticates usually give birth to their young in months when pasture is of high nutrient quality to support them through the stress of lactation. Cattle can breed throughout the year but their reproductive performance changes seasonally with nutritional level being a contributing factor (Mukasa-Mugerwa, 1989; Ezanno, 2005). $\delta^{18}O$ values from serial sampled tooth enamel can be used to identify birth season, and therefore draw conclusions about herder intervention in livestock breeding (Balasse et al., 2003; Balasse and Tresset, 2007; Henton et al., 2010).

In environments with clear seasonal variation in $\delta^{18}O$ of precipitation, birth season can be identified by comparing the $\delta^{18}O$ values at the commencement of mineralisation with the maximum and minimum values within the tooth. It is crucial to have a good understanding of the formation of that tooth for the specific species (Balasse, 2002; Hoppe, 2006; Zazzo et al., 2010). In the Neolithic of north-western Europe, Balasse and Tresset (2007) found that early on in time, birth seasons seemed to be more restricted for both cattle and sheep compared with later in time. The authors could not tell if this was a result of climate or of biological and cultural factors. At Kasteelberg, Balasse et al. (2003) found two lambing seasons per year during the occupation of the site as opposed to the single season that might be expected in a region with a single (winter) rainy season. This observation illustrates the importance of food availability, the role of sheep in the subsistence economy and using sheep mortality profiles in interpreting the seasonal occupation of archaeological sites.

Using $\delta^{15}N$ values from tooth dentine, it is possible to identify weaning ages. This is because the suckling juvenile is on a higher trophic level than the mother and consequentially will have higher $\delta^{15}N$ values. These methods were first used on human skeletons (Fogel et al., 1989; Katzenberg et al., 2002) and later on domesticates (Balasse et al., 2001). Identifying weaning age of domesticates has implications for human intervention in pastoralism. If herders are managing their flocks or herds for dairy and aim to sustain a consistent supply of milk for human consumption, they will intervene in the weaning process. Balasse and Tresset (Balasse and Tresset, 2002) demonstrated early weaning in Neolithic calves, either because Neolithic cows yielded less milk than modern ones and/or as a result of the herders manipulating the weaning process to gain access to a larger milk supply.

4.4.2 Using multiple stable and radiogenic isotopes to infer herd management at Great Zimbabwe

A combination of multiple stable and radiogenic isotopes in animal teeth can be a powerful methodology to infer herd management strategies in the archaeological past. This section proposes how the isotope systems outlined above can be used in combination to address the questions posed in Chapter One.

Second molars in cattle grow incrementally over a period of 24 months. Serially sampling the tooth down the height of the crown and root can provide a high-resolution profile of

diet and environmental conditions during tooth growth. In this study area, stable oxygen isotopes in cattle teeth are most likely to reflect those of drinking water. These animals would have been drinking mostly from rivers, streams and springs which reflect $\delta^{18}O$ of precipitation. Higher altitude areas around Great Zimbabwe receive more rainfall than lower altitude southern Zimbabwe, which should be reflected in different $\delta^{18}O$ values in precipitation in the two areas. Similarly, geological substrates around Great Zimbabwe differ from those of southern Zimbabwe. This should be reflected in the $^{87}Sr/^{86}Sr$ of the soils, and thus the vegetation eaten by the cattle. Given these patterned isotopic differences across the study region, it should be possible to identify seasonal movement of animals by using a combination of $^{87}Sr/^{86}Sr$ and stable oxygen isotopes.

Naturally-occurring grasses in the study region all follow the C_4 photosynthetic pathway, as do the staple grain crops grown and harvested during the occupation of Great Zimbabwe. Residues from these crops are also likely to have been fed to domesticates at times when highly nutritious naturally occurring pasture was not available. Further, the ethnographic record tells us that it is common practice to use domesticated animal dung to fertilize the fields in which crops are grown. This in turn raises the $\delta^{15}N$ values of the crops, and if crops are fed to the cattle, the $\delta^{15}N$ values of the cattle tissues, too, will be higher than in animals which were not fed dung-fertilized crops. Although not the preferred forage, there is some good quality C_3 browse in the study region which is usually consumed in the dry winter season or during drought events. There is especially good C_3 browse in the dry lowveld region of southern Zimbabwe. Seasonal switches in diet between C_4 grasses and C_3 browse can be detected in serially sampled cattle teeth. If we know where the animals were raised from the $^{87}Sr/^{86}Sr$ and $\delta^{18}O$ values, stable carbon and nitrogen isotopes can allow us to infer seasonal diet switching, foddering practices and possibly drought events.

Cattle have the potential to give birth throughout the year, as opposed to other animals which are restricted to a particular season. Manipulation of the calving season, however, requires significant human effort and intervention. If C_3 browse is consumed only in the dry winter months, then the stable carbon isotope trajectories can give insight to season of birth. If the trajectories are the same in all teeth, then it is likely that calves were all born in the same season; if they are different then calves may have been born in different seasons. Similarly, there are expected to be seasonal fluctuations in $\delta^{18}O$ of drinking water: - higher in dry winter months and lower in wet summer months. If the trajectories of

variation in $\delta^{18}O$ are similar in all teeth, we can infer that calves were all born in the same season. If the trajectories are different, calves were likely born in different seasons.

This information is important for a site as significant as Great Zimbabwe, and also has implications for the economic structure of the region as a whole. Smaller sites contemporaneous with Great Zimbabwe and containing similar material culture have been studied to a far lesser extent than Great Zimbabwe itself. Consequently, we know very little of the flow of economic resources between them. Understanding more about the herd management of cattle which were consumed at Great Zimbabwe will provide a new source for insight to potential economic relationships between sites, environmental scenarios and if there was a deliberate attempt to increase the size of herds during the most intensive occupation of Great Zimbabwe.

4.5 Summary

Naturally occurring variations in the stable isotope ratios of light elements provide a natural tracer that can give information on climate, diet and movement of animals through time and space in the archaeological past. There has been relatively little research of this nature in the southern African Iron Age. Multi-isotopic analysis of serial samples of animal teeth provides a high-resolution record of the diet and movement of the animal over a period of one to two years. This information can also be used to address larger questions to do with subsistence strategies, interactions involving trade and exchange, and the rise and decline of centres of economic and political power.

This chapter reviewed the principles of stable light isotope systematics and their application in archaeology, with a focus on herd management strategies in the archaeological past. The next chapter describes the materials and methods employed in this study.

Chapter 5: Materials and Laboratory Methods

5.1 Introduction

This study analysed serial samples of both enamel and dentine from cattle teeth from various excavation areas of Great Zimbabwe. The teeth in this study include recently excavated material and specimens from archived collections housed in the Museum of Human Sciences in Harare, Zimbabwe. This chapter will outline where the teeth were obtained and how the samples were taken. Laboratory procedures for pre-treatment of the samples will be described and finally the procedures used in the mass spectrometry laboratories will be outlined.

5.2 Sampling cattle teeth from Great Zimbabwe

A total of 27 cattle teeth were selected for isotopic analysis from four excavated areas of Great Zimbabwe. Teeth selected were those with the highest (least worn) crowns and the most developed roots, in order to obtain the longest possible records. In order to avoid sampling the same animal more than once, only one tooth type (M2) was selected from each trench as follows:

Fireguard M1: Upper Right M2 (Four teeth)

Eastern Ridge Ruin: Lower Left M2 (Two teeth)

Mujejeje M1: Upper Right M2 (One tooth)

Hodges Midden: Lower Left M2 (20 teeth)

Since these excavation areas are some distance from one another (Figure 5.1), it is unlikely that teeth from different trenches came from the same animal. For comparative purposes, three modern cattle teeth were obtained from a homestead close to Great Zimbabwe in 2018. The stable isotope ratios of these teeth therefore reflect diet from 2016 to 2018.

M2s were divided into five eruption and wear classes (Table 5.1). These are based on Thorp's (1995) synthesis of a variety of sources including Silver's (1969) eruption dates, Grant's (1975) wear stages and Voigt's (1983) eruption and wear classes.

Table 5.1: Eruption and wear classes of M2s (Thorp 1995)

Eruption and wear classes	M2
I	Unerupted
II	Erupting
III	Light wear
IV	Moderate wear
V	Heavy wear

Table 5.2 shows the context, approximate age and number of sub-samples analysed from each tooth.

Table 5.2: Context, age estimate and number of sub-samples per tooth.

Tooth Number	Excavation area	Level	Wear stage	Estimated Age (months)	Number of sub samples strontium	Number of sub samples enamel	Number of sub samples dentine
20217	Fireguard M1	Level 4	III	18-24	26	19	6
20218	Fireguard M1	Level 4	III	18-24	20	18	12
20220	Fireguard M1	Level 4	IV	30-42	15	12	6
20223	Fireguard M1	Level 3	IV	24-30	15	15	8
20226	Mujejeje M1	Level 2	IV	24-30	24	19	6
20228	Eastern Ridge Ruin	Level 5	III	18-24	20	13	15
20231	Eastern Ridge Ruin	Level 7	III	18-24	28	18	10
24083	Hodges Midden	N/A	IV	24-30	20	12	9
24084	Hodges Midden	N/A	II	15-18	20	14	19
24085	Hodges Midden	N/A	II	15-18	24	13	8
24086	Hodges Midden	N/A	II	15-18	27	16	8
24087	Hodges Midden	N/A	III	18-24	23	12	12
24088	Hodges Midden	N/A	II	15-18	22	13	9
24089	Hodges Midden	N/A	III	18-24	23	13	13
24090	Hodges Midden	N/A	III	18-24	24	14	15
24091	Hodges Midden	N/A	III	18-24	21	13	9
24092	Hodges Midden	N/A	III	18-24	22	12	12
24093	Hodges Midden	N/A	III	18-24	22	11	10
24094	Hodges Midden	N/A	II	15-18	19	12	10
24095	Hodges Midden	N/A	II	15-18	26	13	6
24096	Hodges Midden	N/A	II	15-18	23	13	5
24097	Hodges Midden	N/A	III	18-24	23	12	13
24098	Hodges Midden	N/A	II	15-18	28	13	14
24099	Hodges Midden	N/A	III	18-24	24	14	15
24100	Hodges Midden	N/A	III	18-24	17	13	16
24101	Hodges Midden	N/A	II	15-18	26	13	20
24102	Hodges Midden	N/A	II	15-18	27	15	10

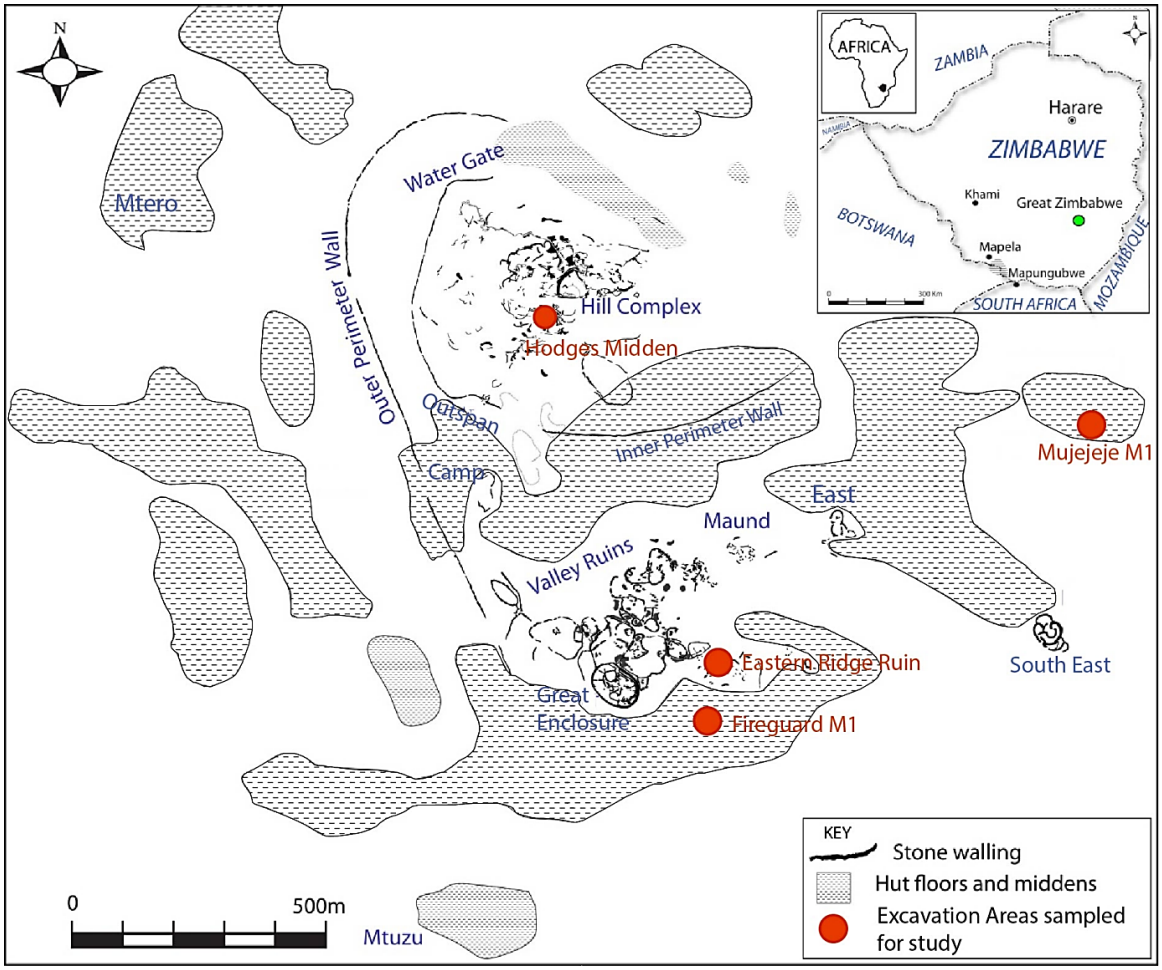


Figure 5.1: Location of excavation areas where cattle teeth were taken

Faunal identification based on morphology alone is somewhat subjective, and DNA techniques are still too expensive to identify many specimens at once. Cattle and buffalo have very similar tooth morphologies although one characteristic which can distinguish them is that buffalo teeth tend to be larger than cattle teeth. As such, tooth measurements were taken from buffalo and cattle comparative faunal specimens in order to be able to identify any buffalo that might have been present among the archaeological teeth. Tooth measurements followed Plug (1989); the length and breadth measurements taken for each tooth are illustrated in Figure 5.2.

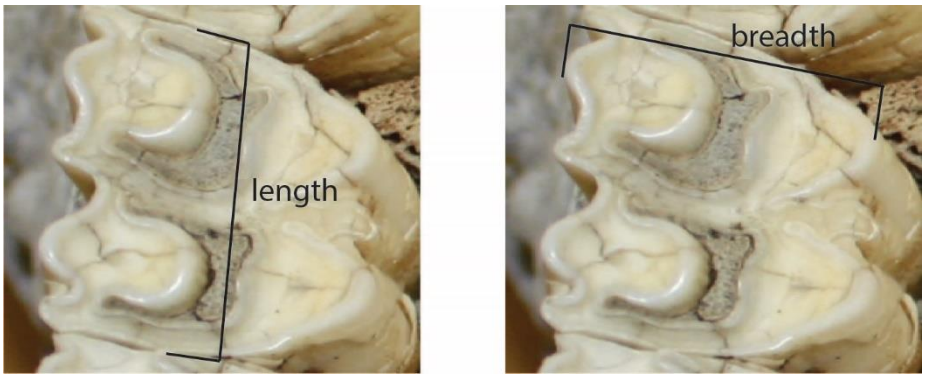


Figure 5.2: Locations of tooth length and breadth measurements for lower M2s (photographed by M. House).

5.3 Sampling, pre-treatment and C and O isotope analysis of enamel

Enamel samples were taken using a 0.5 mm diameter diamond powder-coated drill bit on a Dremel handheld rotary drill. The surface of each tooth was abraded lightly over the area to be sampled to remove surface dirt, then enamel powder was removed from a series of horizontal bands down the height of the crown. Each band (sub-sample of enamel) was approximately 2mm apart and the enamel powder from each weighed between 5-10mg (Figure 5.3). Care was taken to avoid penetrating the dentine beneath the enamel. Dentine was sampled independently, in another sampling procedure, see section 5.4.

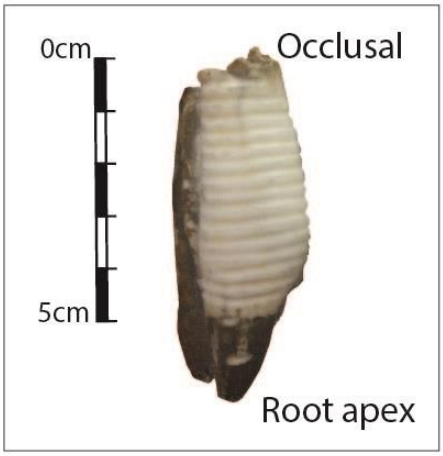


Figure 5.3: Section of cattle tooth after removal of a series of enamel samples for light isotope analysis.

The pre-treatment method used follows that outlined by Lee Thorp et al., (1997), with some modifications. 5-10mg of enamel powder was soaked in 1ml of 1.75% sodium hypochlorite ($NaHClO_3$) for 45 minutes, agitating at intervals, to remove any organic components. After centrifuging and rinsing in distilled water three times, each sample was treated with 0.75ml

0.1M acetic acid (CH_3COOH) for 10 minutes to remove diagenetic carbonates (Loftus and Sealy, 2012). These include any adsorbed carbonates, which are more soluble than structural carbonates and could therefore be removed using this method. Finally, the samples were rinsed three times with distilled water and freeze-dried.

1.8-2.2mg of each pre-treated sample was weighed into a 12ml borosilicate glass tube cleaned with phosphoric acid as described by Loftus and Sealy (2012). The tubes were capped with screw top exetainer caps and flushed with helium using a CTC Analytics A200S auto sampler. Five to seven drops of 100% phosphoric acid were manually added to the sample tubes through the septum using a needle and syringe and left for a minimum of two and a half hours at 72°C. The gas evolved in each tube was sampled by the auto sampler. The purified CO_2 gas was analysed by a Delta Plus XP isotope ratio mass spectrometer (IRMS) controlled by Isodat software.

Precision was monitored by repeated measurements of both in-house (Cavendish marble) and international standards (NBS 18 and NBS 19). Both carbon and oxygen isotope results are reported in standard δ notation relative to PeeDee Belemnite (PDB) in parts per mil (‰). The reproducibility of the repeated measurements was ≤ 0.2‰ for both $\delta^{13}C$ and $\delta^{18}O$ values. $\delta^{13}C$ and $\delta^{18}O$ values of standards for each run are tabled in Appendix 1.

5.4 Sampling, pre-treatment and C and N isotope analysis of dentine

For most individuals, dentine was taken from the same loph of the same tooth sampled for enamel in a separate sampling procedure, but in some cases, the preservation of the dentine was questionable and a different loph was used. Due to the difficulty in separating the enamel from the dentine, an entire quarter of each tooth loph was cut out and placed in 0.2M HCl until demineralisation was complete. This took between 10-20 days. HCl solution was changed every 3 days. Once demineralisation was complete and a soft pseudomorph remained, the enamel was separated from the dentine using a scalpel and discarded. The dentine pseudomorphs were rinsed with distilled water 3 times and placed in 0.1M NaOH for 24 hours to remove base-soluble humic contaminants. Samples were then immersed in distilled water for approximately 7 days, changed every 2 days, until pH remained neutral. Each demineralised dentine loph was then cut into horizontal slices 2-3mm thick, which were freeze-dried.

Approximately 0.5mg of each dentine slice was weighed into a tin capsule and combusted in a Flash 2000 organic elemental analyser at 1020°C. The N_2 and CO_2 gases were passed into a Delta V Plus IRMS via a Conflo IV gas control unit, controlled by Isodat software. Results are reported in standard δ notation in parts per mil (‰). $\delta^{13}C$ values are relative to PeeDee Belemnite (PDB), $\delta^{15}N$ values relative to AIR. Samples were analysed in duplicate and if the duplicates differed by more than 1‰ the samples were re-analysed. In each run, in-house standards (ANU sucrose, valine and choc) were used to assess instrument precision. The reproducibility of repeated measurements of the standards was ≤ 0.2‰ for both $\delta^{13}C$ and $\delta^{15}N$. $\delta^{13}C$ and $\delta^{15}N$ values of standards for each run are tabled in Appendix 2.

5.5 Sampling, pre-treatment and $^{87}Sr/^{86}Sr$ analysis of enamel

$^{87}Sr/^{86}Sr$ was analysed using a Laser Ablation Multi-Collector Inductively Coupled Mass Spectrometer (LA-MC-ICP-MS) housed in the Geological Sciences Laboratory at the University of Cape Town. The methods used are as reported by le Roux et al., (2014), and the NuPlasma HR instrument used in this study is the same as the one used in their study. One or more sections of untreated tooth enamel extending over the height of the tooth crown, from the occlusal surface to the ERJ, were placed in the sample chamber. The chamber measured only 2.5 x 2.5 cm, so was too small to accommodate an entire tooth. The sample chamber was flooded with helium (as a sweep gas) and then mixed with argon using a y-connector prior to injection into the plasma. A flat area of the enamel surface was selected for sampling, avoiding any cracks or crevices. Surface contamination was removed before analysis by sweeping the laser along the analysis path (250µm spot size, 750µm in length). The analysis was performed at a higher energy and slower speed over this line with a narrower beam to avoid surface contamination. Horizontal measurements were taken from the occlusal edge of the tooth to the ERJ every 2mm. In most cases, $^{87}Sr/^{86}Sr$ was measured on the same tooth loph on which $\delta^{13}C_{enamel}$ and $\delta^{18}O_{enamel}$ were measured. Where this was not possible, a different loph was used. Data quality was monitored by analysing a bracketing standard (modern shark tooth) at the start and end of each session. Analyses were referenced to bracketing analyses of the international standard SRM987 using $^{87}Sr/^{86}Sr$ reference value of 0.710255. All strontium isotope data are corrected for isobaric interference at 87 amu using the measured ^{85}Rb and the natural

$^{85}Rb/^{87}Rb$ ratio. Instrumental mass fractionation was corrected using the measured $^{86}Sr/^{88}Sr$ ratio and the exponential law, and a true $^{86}Sr/^{87}Sr$ value of 0.1194. The error associated with these measurements is ±0.0003.

5.6 Creating a strontium isotope baseline

To establish the $^{87}Sr/^{86}Sr$ values for bioavailable strontium in the different geological zones of southern Zimbabwe, samples of modern vegetation were collected in 35 different locations (see Figure 5.4 and Table 5.3). At each sampling area, a total of one handful of plant material was picked from approximately five different plants. These comprised mostly grasses (as the preferred food for cattle) but also included leaves from shrubs and small trees. The sampling sites were distributed over varying geological substrates (as shown on Figure 5.4), and away from areas disturbed by construction (roads and telephone lines), rivers and agriculture. GPS readings were taken at each locality (Table 5.3). Plants were loosely packed in paper bags and allowed to dry out in the bags. In the Geological Sciences Department at the University of Cape Town, each sample was placed in a crucible and ashed in a muffle furnace, starting at 300°C and increasing the temperature in increments of 100°C each hour until it reached 650°C, where it remained at overnight. Approximately 50mg of the resultant ash was weighed into a 7ml Teflon beaker. 4ml of 4:1 2B concentrated HF:HNO_3 was added to each sample, which was then left to digest on a hotplate in the closed Teflon beaker for 48 hours at 140°C. Once digested, the samples were dried down at the same temperature. 2ml 65% 2B HNO_3 was added to the residue in the beaker and dried down again at 140°C. This step was repeated once more, and samples were dried down and re-dissolved in 1.5ml of 2M 2B HNO_3 and left overnight. The strontium was then separated from each sample through column separation chemistry following Pin et al., (1994). Each strontium fraction was dried down, dissolved in 2ml 0.2% HNO_3 and $^{87}Sr/^{86}Sr$ measured on the MC-ICP-MS.

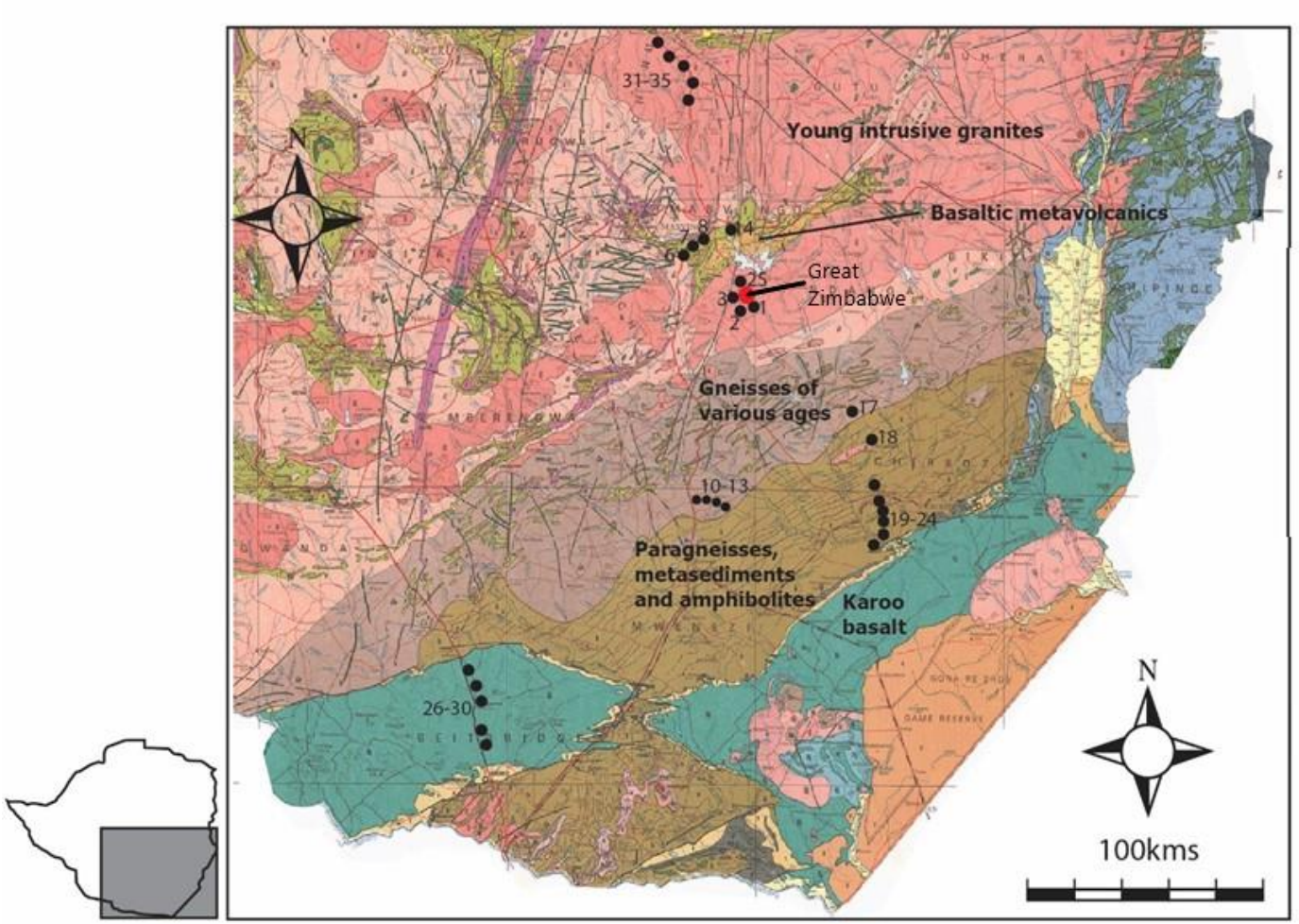


Figure 5.4: Geological map of southern Zimbabwe, with black dots indicating localities where modern vegetation was sampled (Map edited by Neil Rusch)

Table 5.3: GPS co-ordinates and associated geological substrate for each vegetation sample collected for $^{87}Sr/^{86}Sr$ analysis

Geology	**Sample number**	**Colour on Figure 3**	**Geographical coordinates**
Basaltic metavolcanics	6	Light Green	20°12'17"S 30°43'37"E
Basaltic metavolcanics	7	Light Green	20°10'19"S 30°45'49"E
Basaltic metavolcanics	8	Light Green	20°08'50"S 30°46'57"E
Basaltic metavolcanics	14	Light Green	20°06'32"S 30°55'30"E
Gneisses of various ages	10	Grey	21°01'22"S 30°45'57"E
Gneisses of various ages	11	Grey	21°01'09"S 30°48'08"E
Gneisses of various ages	12	Grey	21°01'53"S 30°49'51"E
Gneisses of various ages	13	Grey	21°02'20"S 30°52'03"E
Gneisses of various ages	17	Grey	20°44'48"S 31°23'57"E
Karoo Basalt	26	Blue	21°35'18"S 29°51'59"E
Karoo Basalt	27	Blue	21°38'58"S 29°53'35"E
Karoo Basalt	28	Blue	21°42'06"S 29°54'45"S
Karoo Basalt	29	Blue	21°47'38"S 29°54'52"E
Karoo Basalt	30	Blue	21°51'40"S 29°54'09"E
Paragneisses, metasediments and amphibolite	18	Olive Green	20°49'55"S 31°29'00"E
Paragneisses, metasediments and amphibolite	19	Olive Green	20°58'22"S 31°29'26"E

Paragneisses, metasediments and amphibolite	20	Olive Green	21°01'18"S 31°30'22"E
Paragneisses, metasediments and amphibolite	21	Olive Green	21°04'20"S 31°31'32"E
Paragneisses, metasediments and amphibolite	22	Olive Green	21°06'40"S 31°31'35"E
Paragneisses, metasediments and amphibolite	23	Olive Green	21°08'29"S 31°31'08"E
Paragneisses, metasediments and amphibolite	24	Olive Green	21°10'31"S 31°29'00"E
Younger Intrusive Granite	1	Pink	20°17'54"S 30°56'18"E
Younger Intrusive Granite	2	Pink	20°18'13"S 30°55'05"E
Younger Intrusive Granite	3	Pink	20°16'24"S 30°55'16"E
Younger Intrusive Granite	25	Pink	20°16'02"S 30°55'33"E
Younger Intrusive Granite	31	Pink	19°31'11"S 30°37'04"E
Younger Intrusive Granite	32	Pink	19°33'09"S 30°39'49"E
Younger Intrusive Granite	33	Pink	19°38'52"S 30°45'50"E
Younger Intrusive Granite	34	Pink	19°53'02"S 30°44'37"E
Younger Intrusive Granite	35	Pink	19°57'49"S 30°45'34"E

5.7 Summary

This chapter has outlined the methods used for this study. Sampling strategies employed for light isotope analysis of dentine and enamel tissues were described and pre-treatment for both tissues explained. The collection, sampling protocol and pre-treatment methods for strontium isotope analysis were also described. The next chapter will present the results of the analyses.

Chapter 6: Results

6.1 Introduction

This chapter presents the results of this study. The radiocarbon dates, morphological data and stable isotope results for the 27 teeth from Great Zimbabwe are presented in turn. This is the most rigorous way of presenting these results. Combining C and O, and C and N did not show clear patterns/relationships and so they are presented separately. Summary data is presented in tables within this chapter. All of the data for the 27 archaeological teeth are found in Appendix 3, and those for the 3 modern teeth in Appendix 4.

6.2 Radiocarbon dates

11 of the teeth selected for isotopic analyses were also radiocarbon dated in order to obtain better chronological resolution, both of the midden deposits themselves and to ensure comparison of teeth from similar time periods. Teeth were chosen from different excavation areas and from different trench layers; the dating of the Hodges material is poorly resolved so additional dates were necessary. Teeth which were recovered in the same context as those which were radiocarbon dated were assumed to originate from the same chronological period. Teeth which did not show much visible humic contamination and had structural integrity were selected for stable isotope analyses and radiocarbon dating to increases the chances of collecting well preserved collagen. Collagen was extracted from the dentine and the dates were measured at Beta Analytics in Miami, Florida. Table 6.1 lists the calibrated and uncalibrated dates for each of the 11 specimens. Figure 6.1 is a graphical representation of each calibrated radiocarbon date.

Table 6.1: Radiocarbon dates on dentine collagen from Great Zimbabwe calibrated with OxCal version 4.3.1 using SHCal13 (Hogg et al., 2013)**.**

UCT Lab number	**Excavation Area**	**Beta Lab number**	**Uncalibrated radiocarbon age BP**	**Calibrated date range AD (95.4%)**
20223	Fireguard M1	470724	420±30	1446-1624
20218	Fireguard M1	470723	460±30	1428-1614
20220	Fireguard M1	470720	430±30	1442-1623
20228	Eastern Ridge Ruin	470726	630±30	1304-1415
20231	Eastern Ridge Ruin	470722	610±30	1315-1430
24093	Hodges	496529	630±30	1304-1415
24085	Hodges	492711	580±30	1324-1440
24101	Hodges	492712	550±30	1398-1446
24100	Hodges	492713	1710±30	250-436
24092	Hodges	492715	510±30	1408-1458
24091	Hodges	492716	640±30	1300-1410

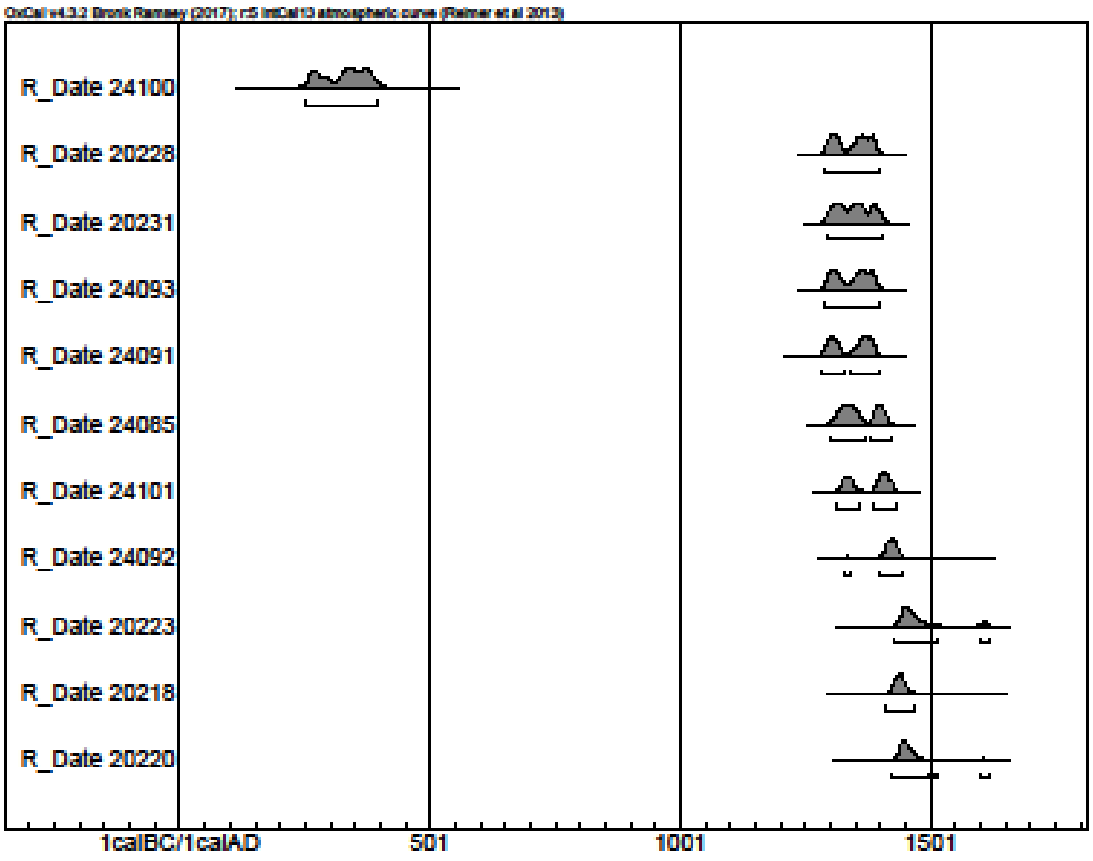


Figure 6.1: Calibrated radiocarbon date ranges per tooth (OxCal v4.3.2 Bronk Ramsey (2017); r:5 IntCal13 atmospheric curve (Reimer et al 2013)

In summary, the specimens (except for the single, older specimen UCT 24100) encompass the period from approximately AD1300 to 1624. The specimens from the Hodges excavation and Eastern Ridge Ruin date to AD1300 to the 1450s (note that the specimens from Eastern Ridge Ruin were stratigraphically located at the bottom of a 2m trench so this does not mean that the Eastern Ridge Ruin occupation ended at AD1430). None of these specimens postdate AD1458 (at the 95.4% confidence level). The specimens from the Fireguard M1 date to AD1428 to the 1620s and thus derive from a slightly later phase of occupation at Great Zimbabwe. These specimens were recovered from Levels 3, 4 and 5 and thus encompass most of the occupation from Fireguard M1.

Note that tooth UCT24100 dates to AD250-436. This is significantly earlier than the other specimens in this study, pre-dating Great Zimbabwe's rise to a major regional centre of power. We know there was an Early Iron Age Gokomere occupation from around AD250 on the hilltop (Huffman, 2007; Pikirayi, 2001; Chirikure et al., 2016), and this tooth presumably relates to that settlement. This date is of considerable interest as it is the earliest radiocarbon date for cattle in this area.

Using a combination of relative and absolute dating principles, the 27 teeth have been assigned to the following time periods:

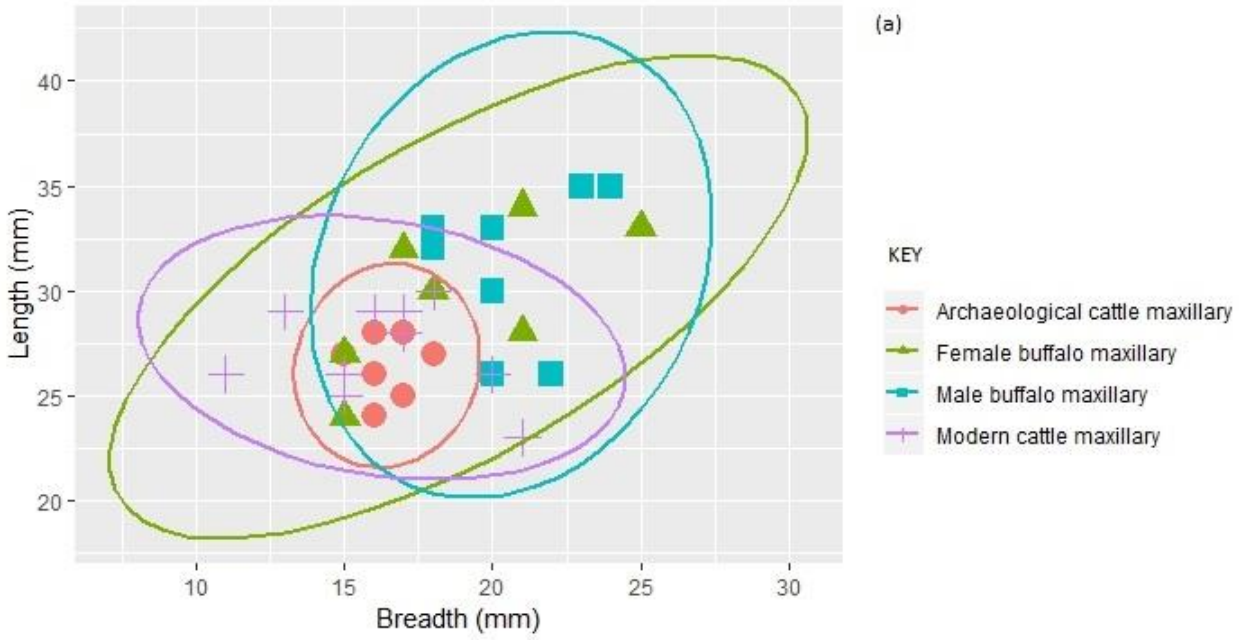
AD250-436: UCT24100

AD1300-1400: UCT20228, 20231, 24083, 24084, 24085, 24086, 24087, 24088, 24089, 24090, 24091, 24093, 24094, 24095, 24096, 24097, 24098, 24099, 24101 and 24102.

AD1400-1600: UCT20217, 20218, 20220, 20223, 20226 and 24092.

6.3 Tooth morphology

Given the possibility of confusion between cattle and buffalo teeth, the lengths and breadths of the archaeological teeth were compared with modern cattle and buffalo teeth from Ditsong Museum. Figure 6.2 shows these results.



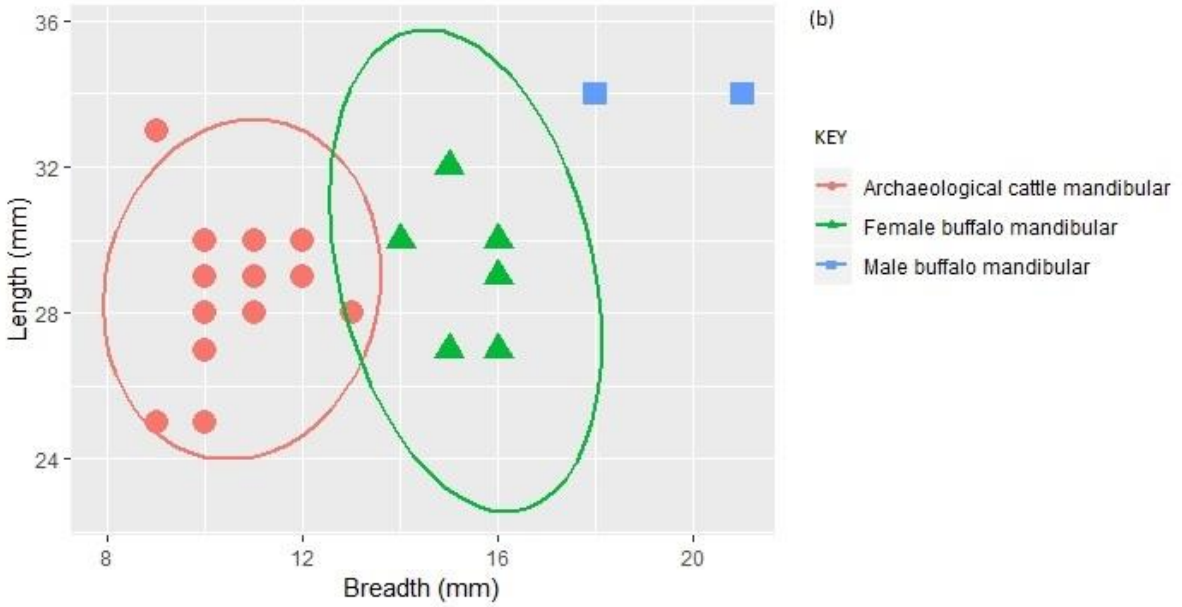


Figure 6.2: Lengths and breadths of (a) maxillary and (b) mandibular second molars from modern cattle and buffalo (from Ditsong Museum) compared with archaeological teeth in this study. All ellipses show a 95% confidence interval.

Individual measurements for each tooth are listed in Tables 6.2 and 6.3. The teeth are divided into maxillary (Figure 6.2a) and mandibular (Figure 6.2b) M2s. The female buffalo maxillary M2s have a mean length of 29 ± 3mm (range of 24 to 34mm, n=7) and mean breadth of 19 ± 3mm (range of 15 to 25mm, n=7). Male buffalo maxillary M2s have a mean length of 31 ± 3mm (range of 26 to 35mm, n=8) and breadth of 20 ± 2mm (range of 18 to 24mm, n=8). In the museum, cattle M2 specimens were not differentiated into male or female and will therefore be treated as one unit, with a mean length of 27 ± 2mm (range of 23 to 30mm, n=11) and mean breadth of 16 ± 2mm (range of 11 to 21mm, n=11). The archaeological M2s in this study have a mean length of 26 ± 1mm (range of 24 to 28mm, n=7) and mean breadth of 16 ± 1mm (range of 15 to 17mm, n=7). The archaeological maxillary M2s fall within the same range as two of the female buffalo teeth (Figure 6.2a). These two smallest female buffalo come from the Marikana area of South Africa. The comparative buffalo came from different areas, so the size range may be greater than would be seen in animals from a single environment.

Table 6.2: Measurements and summary statistics of maxillary tooth lengths and breadths for specimens in Figure 6.2(a)

UCT tooth number	Archaeological cattle (mm)		Museum Accession Number	Female buffalo (mm)		Museum Accession Number	Male buffalo (mm)		Cattle Breed	Modern cattle (mm)	
	length	breadth		length	breadth		length	breadth		length	breadth
20217	26	16	TM13185	28	21	TM11565	35	23	Pedi Blue	29	16
20218	27	18	TM17750	27	15	TM11565	35	24	Pedi Blue	25	15
20220	28	16	TM3313	24	15	AZ3117	26	22	Nguni	26	11
20223	25	17	TM3313	30	18	AZ3117	26	20	Nguni	28	17
20226	27	15	TM3311	32	17	TM3310	33	18	Nguni	29	16
			TM3311	33	25	TM3312	33	20	Nguni	29	17
			TM17750	34	21	TM3312	32	18	Nguni	30	18
						TM930	30	20	Nguni	26	20
									Nguni	23	21
									Pedi Blue	29	13
									Pedi Blue	26	15
Maximum	28	18		34	25		35	24		30	21
Minimum	24	15		24	15		26	18		23	11
Range	4	2		10	10		9	6		7	10
Mean	26	16		30	19		31	21		27	16
Stdev	1	1		4	4		4	2		2	3

Generally, the mandibular M2s are smaller in length and breadth than the maxillary M2s. The female buffalo mandibular M2 mean length is 26 ± 1mm (range of 27 to 32mm, n=6) and mean breadth 14 ± 1mm (range of 14 to 16mm, n=6). Male buffalo mandibular M2 mean length is 34mm (n=2) and mean breadth is 20 ± 2mm (range of 18 to 21mm, n=2). There were no mandibular cattle M2s available to measure; however, as shown in Figure 6.1b, the breadths of the archaeological mandibular M2s fall outside the range of the buffalo teeth. Their mean length is 28 ± 1mm (range of 25 to 32mm, n=20) and mean breadth is 10 ± 1mm (range of 9 to 13mm, n=20). Figure 6.1b shows that the lengths of the archaeological cattle teeth fall within the range of the buffalo, however the breadths are (in all cases except one) smaller than buffalo. Based on this sample, cattle mandibular M2s are distinguishable from buffalo by their narrower breadths.

Table 6.3: Measurements and summary statistics of mandibular tooth lengths and breadths for specimens in Figure 6.2(b)

UCT Number	Archaeological cattle (mm)		Accession number	Female buffalo (mm)		Accession number	Male buffalo (mm)	
	length	breadth		length	breadth		length	breadth
20228	25	9	TM13185	27	15	TM11565	34	21
20231	28	11	TM13185	30	16	TM11565	34	18
24083	30	11	TM3313	29	16			
24084	29	10	TM3311	27	16			
24085	29	10	TM3313	30	14			
24086	27	10	TM3311	32	15			
24087	29	12						
24088	28	13						
24089	28	11						
24090	28	11						
24091	30	10						
24092	29	12						
24093	29	11						
24094	29	12						
24095	25	10						
24096	30	11						
24097	30	12						
24098	29	10						
24099	28	10						
24100	33	9						
24101	29	11						
24102	30	11						
Maximum	33	13		32	16		34	21
Minimum	25	9		27	14		34	18
Range	8	4		5	2		0	3
Mean	29	11		29	15		34	20
Stdev	2	1		2	1		0	2

Cattle overwhelmingly dominate the faunal material recovered from Great Zimbabwe, with 1330 cattle compared with only 10 wild animals identified from the Hodges Midden (Brain 1974). The archaeological teeth studied here can therefore be assigned with a high degree of confidence to cattle rather than buffalo.

6.4 $\delta^{13}C$ values of serial samples of enamel and dentine

6.4.1 $\delta^{13}C_{enamel}$ values

$\delta^{13}C_{enamel}$ values for all 364 serial samples are tabled in Appendix 3. They range from 3.3 to -2.9‰ with a mean of 1.31 ±1.24‰ indicating a strong C_4 grass diet (see Figure 6.3). Table 6.4 provides summary values for each tooth.

Table 6.4: Summary $\delta^{13}C_{enamel}$ values per tooth

Tooth Number	$\delta^{13}C_{enamel}$ (‰)			
	Maximum	Minimum	Mean	Amplitude
20217	2.2	1.3	1.73	0.9
20218	1.8	1.0	1.38	0.8
20220	2.9	2.4	2.71	0.5
20223	2.5	1.0	1.70	1.5
20226	2.9	2.0	2.45	0.9
20228	3.3	2.8	3.03	0.5
20231	2.6	0.3	1.49	2.3
24083	2.4	1.9	2.09	0.5
24084	2.6	0.3	1.73	2.3
24085	2.1	0.0	1.03	2.1
24086	1.7	-0.4	0.63	2.1
24087	0.9	-2.2	-0.89	3.1
24088	2.4	1.7	2.08	0.7
24089	0.7	-1.5	-0.37	2.2
24090	-2.0	-2.5	-2.37	0.5
24091	1.5	0.6	1.04	0.9
24092	2.8	1.8	2.39	1.0
24093	2.5	1.9	2.21	0.6
24094	0.6	-2.9	-0.77	3.5

24095	2.0	0.7	1.52	1.3
24096	1.4	1.3	1.34	0.1
24097	1.3	0.3	0.92	1.0
24098	2.0	1.2	1.60	0.8
24099	2.8	2.2	2.47	0.6
24100	1.6	0.0	0.55	1.6
24101	1.3	1.1	1.23	0.2
24102	1.4	1.1	1.24	0.3

The individual represented by UCT 24090 has the most negative $\delta^{13}C$ values ($\delta^{13}C$ range -2.5 to -2.0‰). There are four individuals (Figure 6.3: UCT 24090, 24087, 24094 and 24089) which yielded the most negative $\delta^{13}C$ values of less than -1‰. These specimens date to AD1300-1400. The remainder of the individuals show $\delta^{13}C$ values which lie towards the positive end of the range seen in this dataset, indicating a strong grass-based diet. This group includes the specimens dating to AD1400-1600 (Figure 6.3: UCT 20217, 20218, 20220, 20223 and 20226). Sample UCT24100 dating to AD250-400 also falls within the range of the other samples, so its $\delta^{13}C$ values do not stand out in any way.

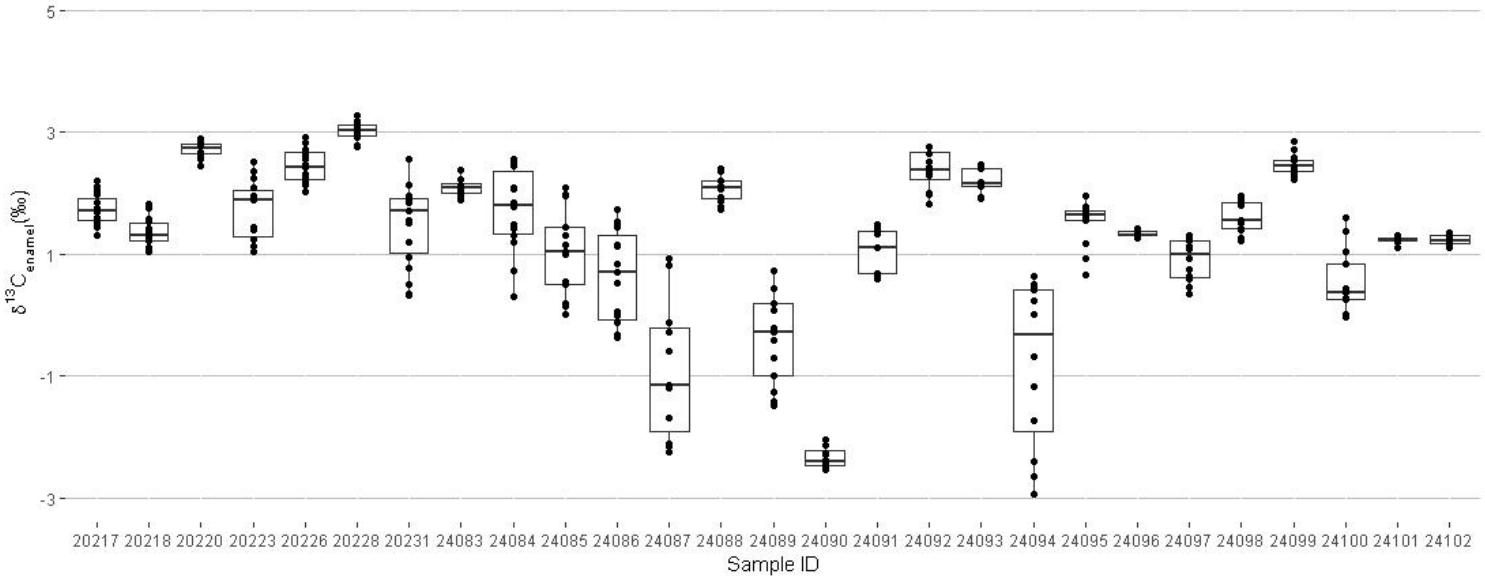


Figure 6.3: Boxplot for $\delta^{13}C_{enamel}$ values per tooth

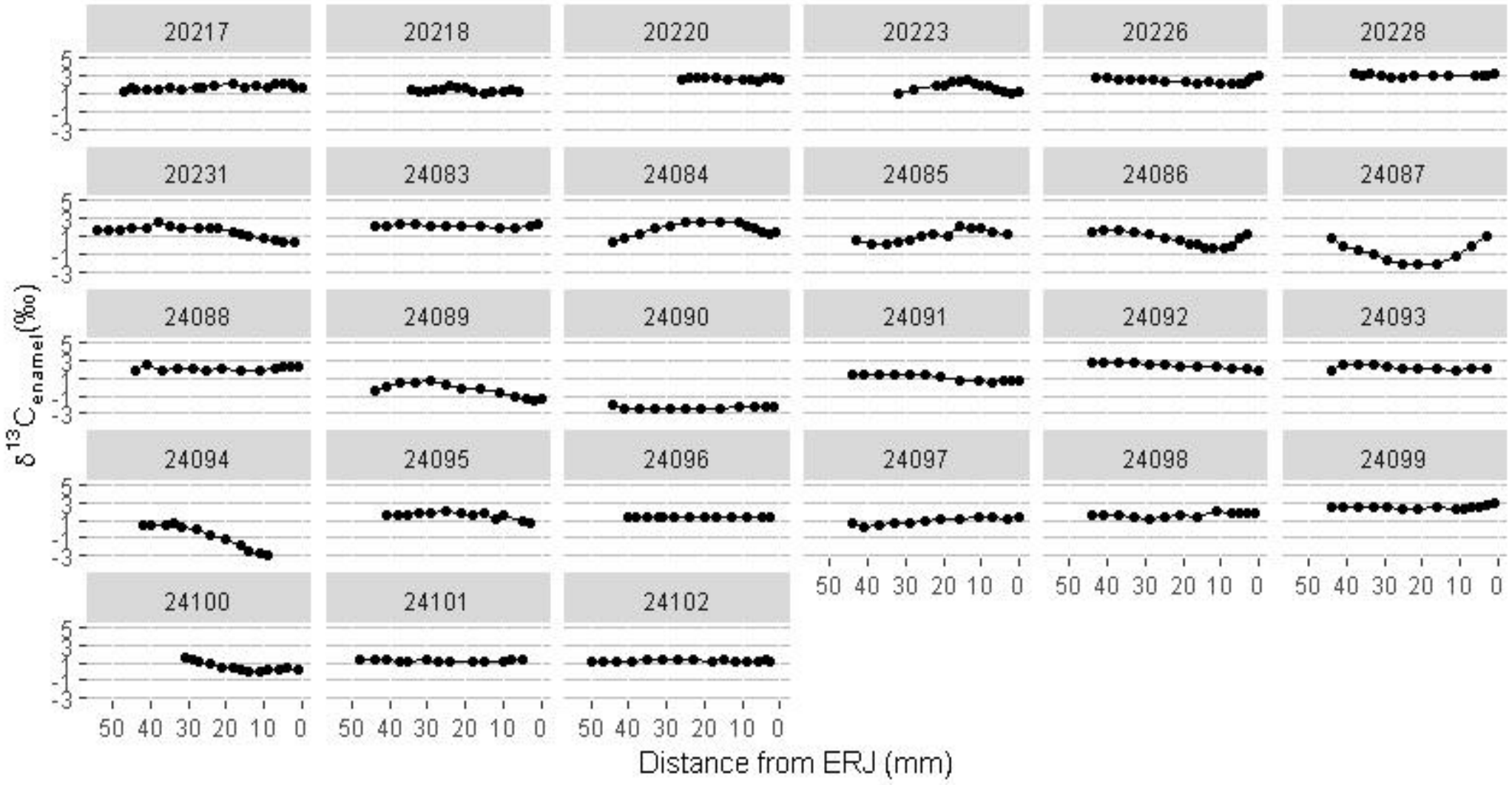


Figure 6.4: $\delta^{13}C_{enamel}$ values for serial samples of 27 archaeological teeth. Point 'zero' on the x-axis indicates the position of the ERJ.

The $\delta^{13}C$ values for 17 individuals show intra-tooth variation of ≤ 1‰ for (Figure 6.4, 20217, 20218, 20220, 20226, 20228, 24083, 24088, 24090, 24091, 24092, 24093, 24096, 24097, 24098, 24099, 24101, 24102) indicating that their diet did not change much over the period of the year that the tooth crown grew. The $\delta^{13}C_{enamel}$ values are generally quite high (mean $\delta^{13}C_{enamel}$ of 228 samples from 17 specimens= 1.61±1.13‰) although one individual (24090) consistently has much lower $\delta^{13}C_{enamel}$ values than the remainder of the teeth.

10 individuals show intra-tooth variation of between 1 and 3.5‰ over the one-year period that the tooth grew (see Figure 6.4, 20223, 20226, 20231, 24084, 24085, 24086, 24087, 24089, 24094, 24095). Their combined mean $\delta^{13}C_{enamel}$ value (0.43±1.33‰ for all 140 samples) is lower than the first group. Specimen 24094 has the maximum amplitude of variation of all the individuals of 3.5‰.

Specimens 24086 and 24087 have more positive $\delta^{13}C_{enamel}$ values at the occlusal end of the tooth, and less positive $\delta^{13}C_{enamel}$ values in the mid-portion of the tooth with more positive values at the ERJ. Specimens 24094 and 24089 have positive values at the occlusal end of the tooth and less positive $\delta^{13}C_{enamel}$ values at the ERJ.

6.4.2 $\delta^{13}C_{dentine}$ values

Collagen quality was evaluated according to the criteria of Ambrose (1990) and van Klinken (1999) (C:N elemental ratio between 2.9 and 3.6, weight %C 26-47% and weight %N 11-17%). Only samples which met these criteria were used in this study as presented in Appendix 3 and 4. All results for modern teeth have been corrected for the fossil fuel effect by adding 1.5‰ to the measured values.

Summary $\delta^{13}C_{dentine}$ results for the three modern cattle teeth are presented in Table 6.5. The results range from -10.2‰ to -6.5‰, showing inclusion of browse in the two years of tooth growth (from the crown and root portion). The 50 modern $\delta^{13}C_{dentine}$ serial samples show within-tooth variation of less than 2.9‰ (Figure 6.5). The $\delta^{13}C_{dentine}$ values for all 296 archaeological samples are listed in Appendix 3. They range from -12.6‰ to -5.4‰ (mean of all samples= -7.48 ± 1.17‰) over two years of tooth growth. The summary data is presented in Table 6.6.

Table 6.5: Summary $\delta^{13}C_{dentine}$ values for modern teeth (corrected for the fossil fuel effect)

Tooth Number	$\delta^{13}C_{dentine}$ (‰)						
	Maximum	Minimum	Mean	Amplitude	Mean %C	Mean %N	C:N ratio
24142	-6.8	-9.0	-7.75	2.2	44.0	14.9	3.4
24143	-7.3	-10.2	-8.19	2.9	39.6	14.7	3.2
24144	-6.5	-8.6	-7.41	2.1	43.7	14.5	3.4

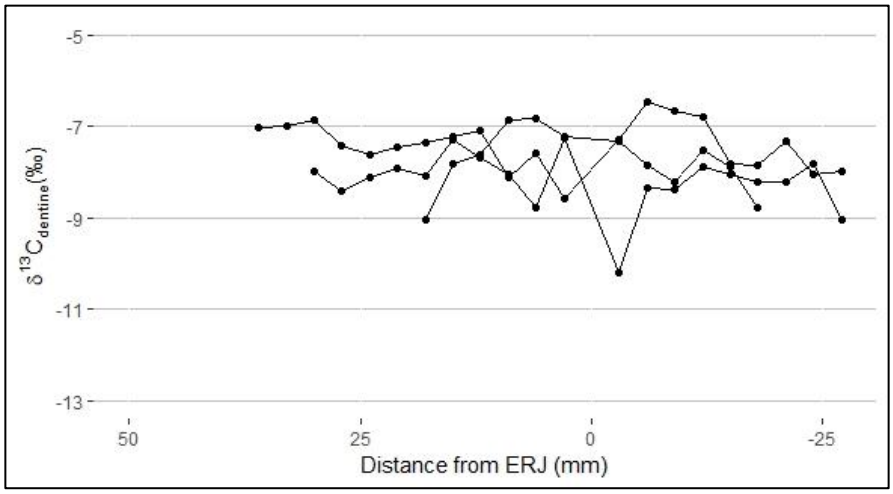


Figure 6.5: Serial $\delta^{13}C_{dentine}$ values for 3 modern teeth (corrected for the fossil fuel effect). Point 'zero' on the x-axis indicates the position of the ERJ.

Table 6.6: Summary $\delta^{13}C_{dentine}$ values for archaeological teeth

Tooth Number	$\delta^{13}C_{dentine}$ (‰)						
	Maximum	Minimum	Mean	Amplitude	Mean %C	Mean %N	C:N atomic ratio
20217	-6.7	-7.3	-6.98	0.5	40.8	13.6	3.3
20218	-6.4	-7.5	-6.87	1.1	38.5	13.7	3.3
20220	-6.0	-8.2	-7.10	2.2	37.4	13.1	3.3
20223	-7.9	-9.9	-8.56	2.1	29.1	11.6	3.3
20226	-6.2	-7.2	-6.71	1.0	37.3	12.5	3.5
20228	-6.0	-6.5	-6.15	0.6	44.1	15.9	3.2
20231	-5.9	-7.8	-7.07	1.9	37.5	13.3	3.3
24083	-6.0	-7.9	-6.62	1.9	34.7	11.5	3.3
24084	-6.2	-8.6	-7.27	2.3	37.0	12.8	3.3
24085	-7.0	-8.2	-7.51	1.2	35.9	12.8	3.3
24086	-8.0	-10.1	-8.66	2.1	39.7	14.5	3.2
24087	-6.9	-10.2	-8.58	3.4	33.6	11.5	3.4
24088	-5.4	-7.1	-6.17	1.8	35.9	13.7	3.2
24089	-7.9	-9.6	-8.90	1.6	39.4	14.1	3.3
24090	-8.2	-12.6	-9.95	4.4	39.3	14.3	3.2
24091	-7.0	-8.1	-7.64	1.1	38.2	13.3	3.3
24092	-6.1	-7.9	-7.10	1.8	40.5	14.7	3.2
24093	-6.2	-7.8	-6.82	1.6	43.7	15.7	3.3
24094	-8.7	-11.9	-9.74	3.2	35.7	12.7	3.3
24095	-7.2	-7.5	-7.42	0.3	35.7	14.1	2.9
24096	-6.3	-6.9	-6.64	0.6	35.9	12.1	3.4
24097	-6.7	-8.5	-7.34	1.7	36.0	12.9	3.3
24098	-6.9	-8.1	-7.37	1.3	37.0	13.5	3.3
24099	-5.7	-8.0	-6.78	2.2	36.4	12.7	3.3
24100	-6.5	-8.4	-7.39	2.0	39.7	14.4	3.2
24101	-5.8	-7.5	-6.93	1.7	43.7	15.7	3.2
24102	-6.7	-7.8	-7.31	1.1	42.1	15.2	3.2

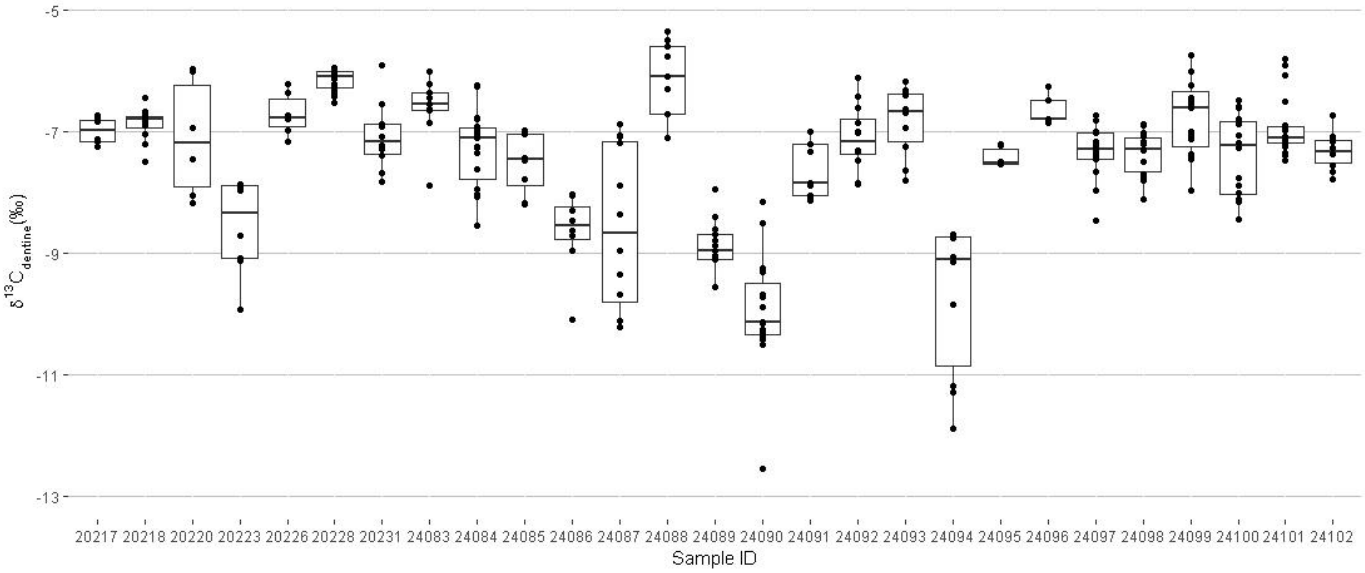


Figure 6.6: Box plot for $\delta^{13}C_{dentine}$ values per tooth

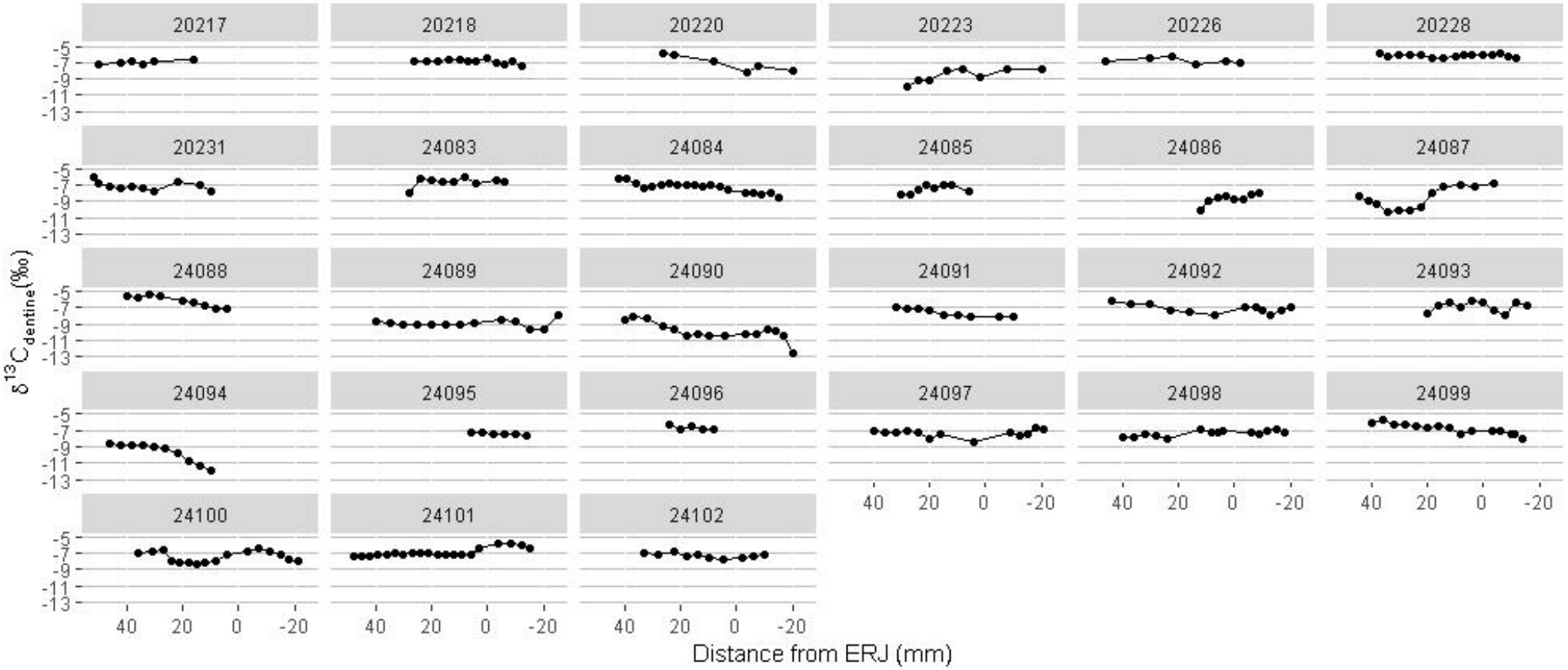


Figure 6.7: Serial $\delta^{13}C_{dentine}$ values for 27 archaeological teeth. Point 'zero' on the x-axis indicates the position of the ERJ.

Nine individuals showed amplitudes of variation of between 2‰ and 4.4‰ over the period of tooth formation (20220, 20223, 24084, 24086, 24087, 24090, 24094, 24099, 24100, Figure 6.7). These individuals consumed varying amounts of browse and graze throughout tooth formation and have a mean $\delta^{13}C_{dentine}$ value of -8.17±1.41‰. The individual with the greatest amplitude of variation is 24090 with a difference of 4.4‰. The remainder of the individuals' $\delta^{13}C_{dentine}$ values do not fluctuate much, with intra-tooth variation of less than 2‰. They have a more positive mean $\delta^{13}C_{dentine}$ value of -7.11±0.76.

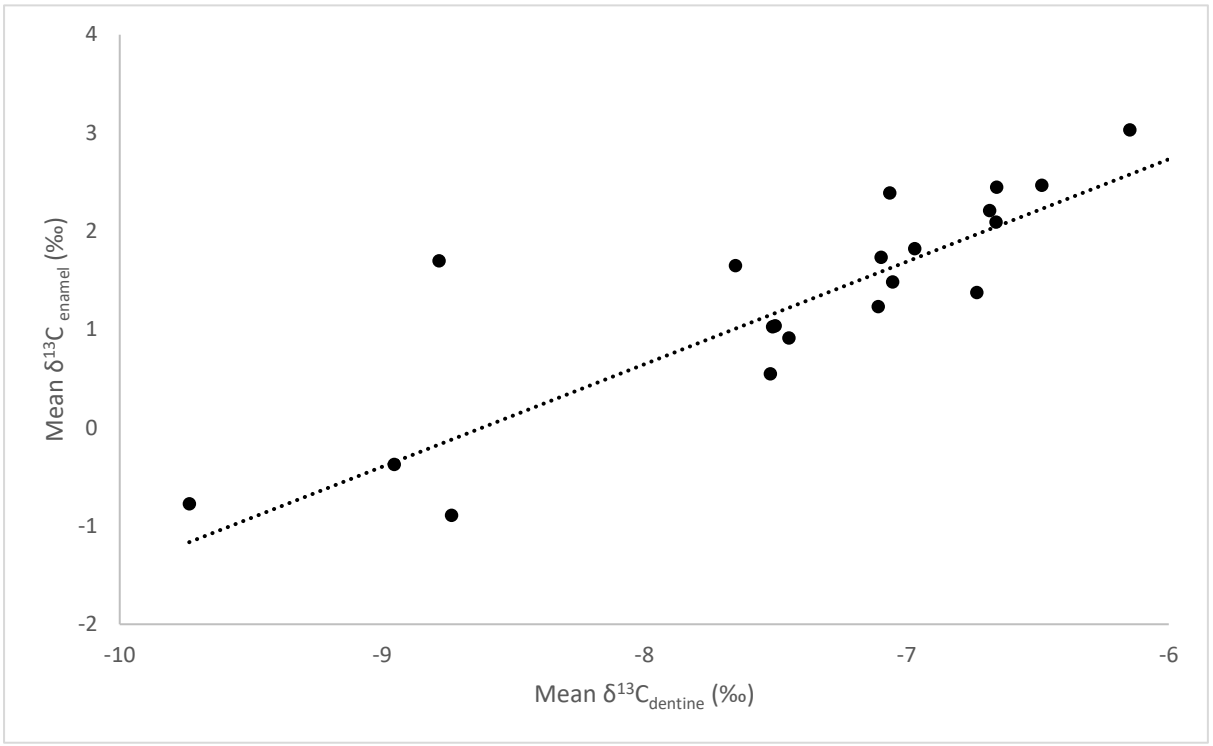
At the occlusal surface of UCT24087 there is a strong decrease in $\delta^{13}C$ values. Although the dentine record for UCT24086 is shorter, it also has lower $\delta^{13}C$ values at the early-forming portion of the tooth followed by an increase. UCT24085 and UCT20220 show an increase in $\delta^{13}C$ values followed by consistently high values. These individuals may have been born in a different season.

6.4.3 Comparing stable carbon isotopes in enamel and dentine

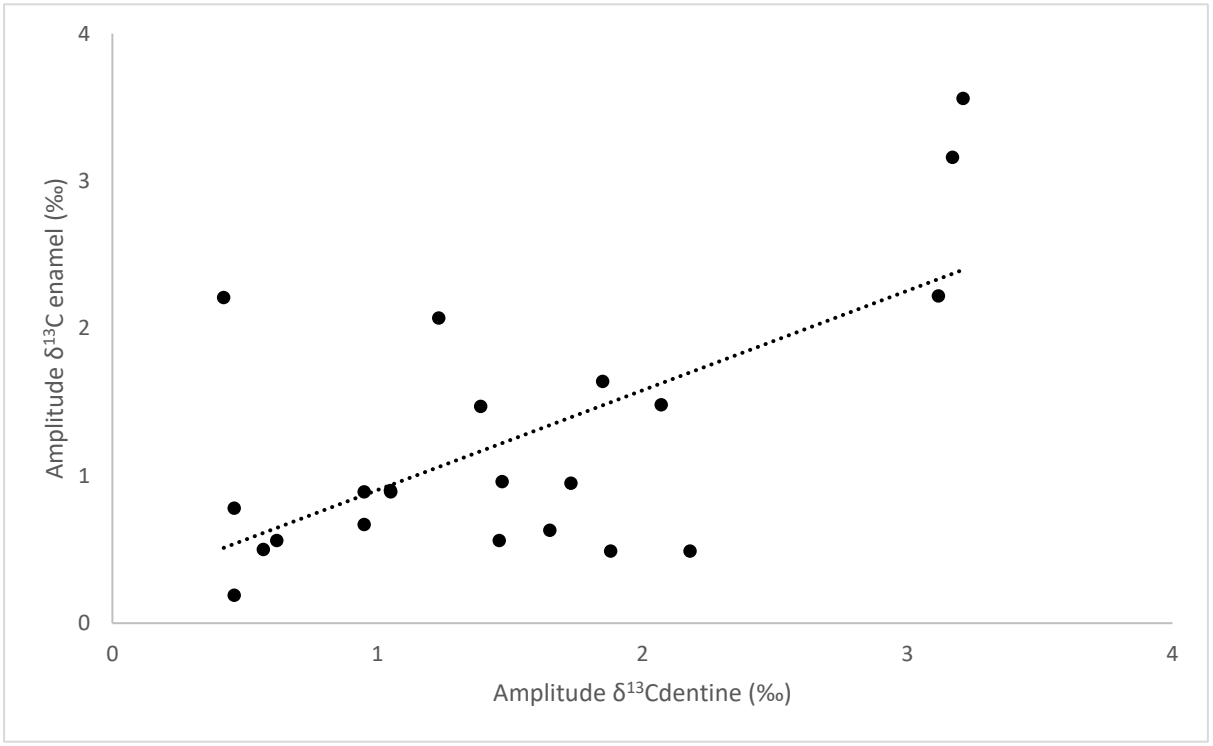
In order to compare the $\delta^{13}C$ values in dentine and enamel, 22 out of 27 teeth will be discussed. This is because in 5 teeth, the number of dentine collagen sub-samples was considerably lower than the enamel sub-samples, making it difficult to compare the two. $\delta^{13}C_{enamel}$ for 296 enamel samples taken from all 22 M2s range from -2.9‰ to 3.3‰ (See Table 6.7), with a mean of 1.28 ± 1.32 ‰, showing that the animals consumed mainly C_4 grasses. The range of values for all 192 $\delta^{13}C_{dentine}$ samples analysed in the crown portion of the tooth is -11.9‰ to -5.4‰ with a mean of -7.46 ± 1.20 ‰, leading to the same conclusion. The difference between the mean enamel and mean dentine values per tooth (mean $\Delta^{13}C_{enamel\text{-}dentine}$) ranges from 7.3 to 10.5‰, with a median of 8.7 ‰ (Table 6.7). Note that, because dentine and enamel samples are not paired (and differences in time-averaging and enamel maturation would make it meaningless to do so) this statistic cannot be presented per slice. Maximum within-tooth variation in $\delta^{13}C_{enamel}$ (henceforth referred to as "$\delta^{13}C_{enamel}$ amplitude") for all 22 teeth ranges from 0.2‰ to 3.6‰, with a mean of 1.34 ± 0.87‰. Maximum within-tooth variation in $\delta^{13}C_{dentine}$ ("$\delta^{13}C_{dentine}$ amplitude") ranges from 0.4‰ to 3.2‰, with a mean of 1.52 ± 0.82 ‰.

Table 6.7: Summary $\delta^{13}C$ values for 22 archaeological teeth (enamel and dentine)

	Enamel $\delta^{13}C$ (‰)				Dentine(crown) $\delta^{13}C$ (‰)								
Tooth Number	Max	Min	Amplitude	Mean	Max	Min	Amplitude	Mean	Mean Δ 13C enamel-dentine (‰)	Δ13C enamel-dentine amplitude (‰)	Mean wt % N	Mean wt % C	C:N ratio (atomic)
20217	2.2	1.3	0.9	1.7	-6.7	-7.3	0.5	-6.98	8.7	0.4	14.3	40.8	3.3
20218	1.8	1.1	0.8	1.4	-6.4	-6.9	0.5	-6.73	8.1	0.3	14.2	40.1	3.3
20223	2.5	1.0	1.5	1.7	-7.9	-9.9	2.1	-8.78	10.5	-0.6	11.8	28.7	3.3
20226	2.9	2.0	0.9	2.4	-6.2	-7.2	1.0	-6.66	9.1	-0.1	12.4	36.8	3.5
20228	3.3	2.7	0.6	3.0	-6.0	-6.5	0.6	-6.15	9.2	0.0	15.7	43.9	3.2
20231	2.5	0.3	2.2	1.4	-5.9	-7.8	1.9	-7.2	8.6	0.3	13.5	37.5	3.3
24083	2.4	1.9	0.5	2.1	-6.0	-7.9	1.9	-6.66	8.8	-1.4	12.3	34.3	3.3
24084	2.6	1.1	1.5	1.8	-6.2	-7.6	1.4	-6.97	8.8	0.1	13.4	38.4	3.4
24085	2.1	0.0	2.1	1.0	-7.0	-8.2	1.2	-7.51	8.5	0.8	12.8	35.9	3.3
24087	0.9	-2.2	3.2	-0.9	-7.1	-10.2	3.2	-8.73	7.8	0.0	11.9	33.9	3.4
24088	2.4	1.7	0.7	2.1	-5.4	-7.1	1.8	-6.17	8.2	-1.1	13.7	35.9	3.2
24089	0.7	-1.5	2.2	-0.4	-8.7	-9.1	0.4	-8.95	8.6	1.8	14.1	40.1	3.3
24090	-2.0	-2.5	0.5	-2.3	-8.2	-10.4	2.2	-9.58	7.3	-1.7	14.3	39.2	3.2
24091	1.5	0.6	0.9	1.0	-7.0	-8.1	1.1	-7.50	8.5	-0.2	13.8	39.0	3.3
24092	2.8	1.8	1.0	2.4	-6.1	-7.8	1.7	-7.06	9.5	-0.8	14.8	40.4	3.2
24093	2.5	1.9	0.6	2.2	-6.2	-7.6	1.5	-6.68	8.9	-0.9	15.7	43.6	3.2
24094	0.6	-2.9	3.6	-0.8	-8.7	-11.9	3.2	-9.74	9.0	0.3	12.9	35.7	3.3
24097	1.3	0.3	1.0	0.9	-7.0	-8.5	1.5	-7.45	8.4	-0.5	13.1	35.6	3.3
24098	2.0	1.4	0.6	1.7	-6.9	-8.1	1.2	-7.48	9.1	-0.7	12.9	35.9	3.3
24099	2.9	2.2	0.6	2.5	-5.7	-7.4	1.7	-6.48	9.0	-1.0	12.3	35.6	3.4
24100	1.6	0.0	1.6	0.5	-6.6	-8.4	1.9	-7.52	8.1	-0.2	14.5	40.0	3.2
24101	1.3	1.1	0.2	1.2	-6.9	-7.4	0.5	-7.11	8.3	-0.3	15.6	43.6	3.2



(a)



(b)

Figure 6.8(a): Mean $\delta^{13}C_{enamel}$ (‰) vs mean $\delta^{13}C_{dentine}$ (‰) for each tooth (b): $\delta^{13}C_{enamel}$ amplitude (‰) vs $\delta^{13}C_{dentine}$ amplitude per tooth (‰)

Mean $\delta^{13}C_{enamel}$ and $\delta^{13}C_{dentine}$ values are strongly correlated ($R^2 = 0.9$, Figure 6.8a). There is, however, a weaker correlation between $\delta^{13}C_{enamel}$ amplitude and $\delta^{13}C_{dentine}$ amplitude ($R^2 = 0.6$, Figure 6.8b). In other words, there is a good relationship between the mean $\delta^{13}C_{enamel}$ and $\delta^{13}C_{dentine}$ values in serial samples of the same tooth, however, a poorer relationship between the amplitude of $\delta^{13}C_{enamel}$ and $\delta^{13}C_{dentine}$ values the same tooth.

To explore within-individual variation in $\delta^{13}C_{enamel}$ compared with $\delta^{13}C_{dentine}$ values, the serial samples from both tissues have been plotted per tooth (Figures 6.9-6.11). The teeth are separated into three groups on initial observation. Group 1 consists of individuals that show relatively low amplitude variation in both $\delta^{13}C_{dentine}$ (<1‰) and $\delta^{13}C_{enamel}$ (<1‰) (Figure 6.9). Group 2 consists of individuals that show relatively higher amplitude variation in $\delta^{13}C_{dentine}$ (>1‰) in combination with low amplitude variation in $\delta^{13}C_{enamel}$ (<1‰) (Figure 6.10). Group 3 consists of individuals that show relatively high amplitude variation in both $\delta^{13}C_{dentine}$ (>1‰) and $\delta^{13}C_{enamel}$ (>1‰) (Figure 6.11).

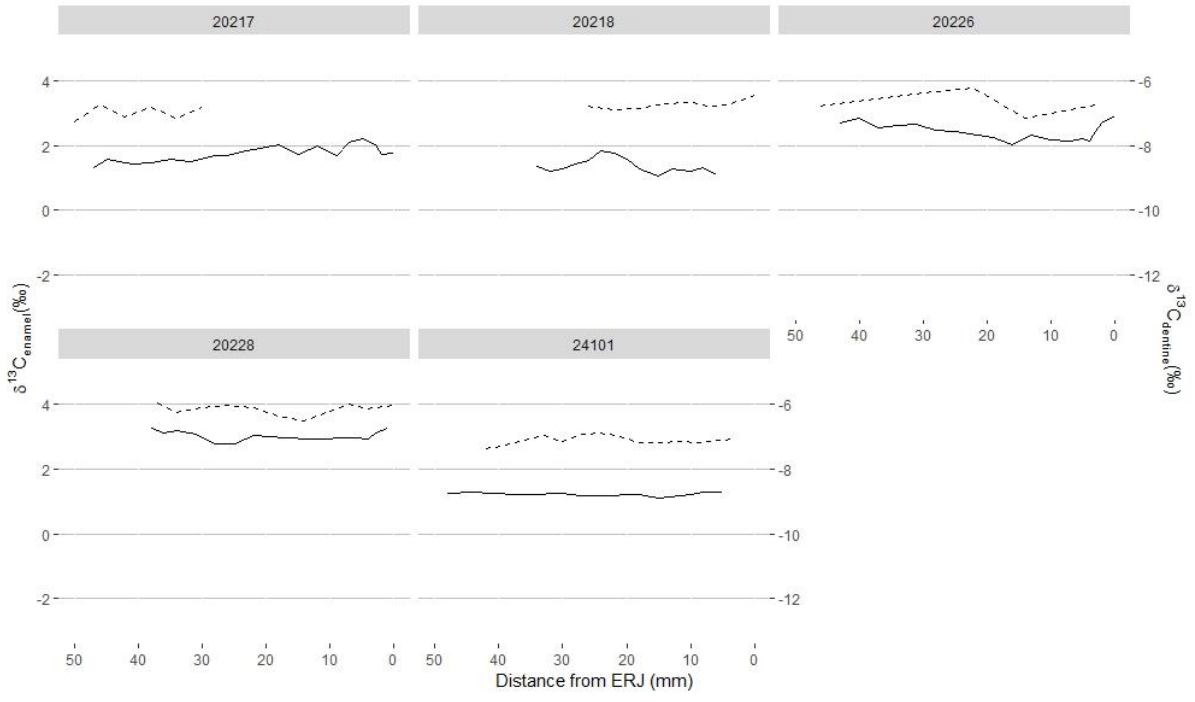


Figure 6.9: Group 1 serial samples. Low amplitude variation in both enamel (<1‰) and dentine (<1‰). Note that the closer the $\delta^{13}C_{enamel}$ and $\delta^{13}C_{dentine}$ lines are to each other, the higher the $\Delta^{13}C_{enamel\text{-}dentine}$. Dashed line represents dentine, solid line represents enamel.

Figure 6.9 illustrates the $\delta^{13}C_{enamel}$ and $\delta^{13}C_{dentine}$ values for five individuals which display little within-tooth variation, here designated Group 1. All the $\delta^{13}C_{enamel}$ values are >0‰ indicating a diet dominated by C_4 grass. This is corroborated by the $\delta^{13}C_{dentine}$ values which are almost all > -8‰ (except for 24090). There was little seasonal fluctuation in the diets of these individuals over the year the tooth crown formed. In this group, there is no major shift in the $\delta^{13}C$ values in one tissue which cannot be seen in the other. The difference between the amplitudes of $\delta^{13}C_{enamel}$ and $\delta^{13}C_{dentine}$ is not significant (Mann Whitney-U test, p>0.05).

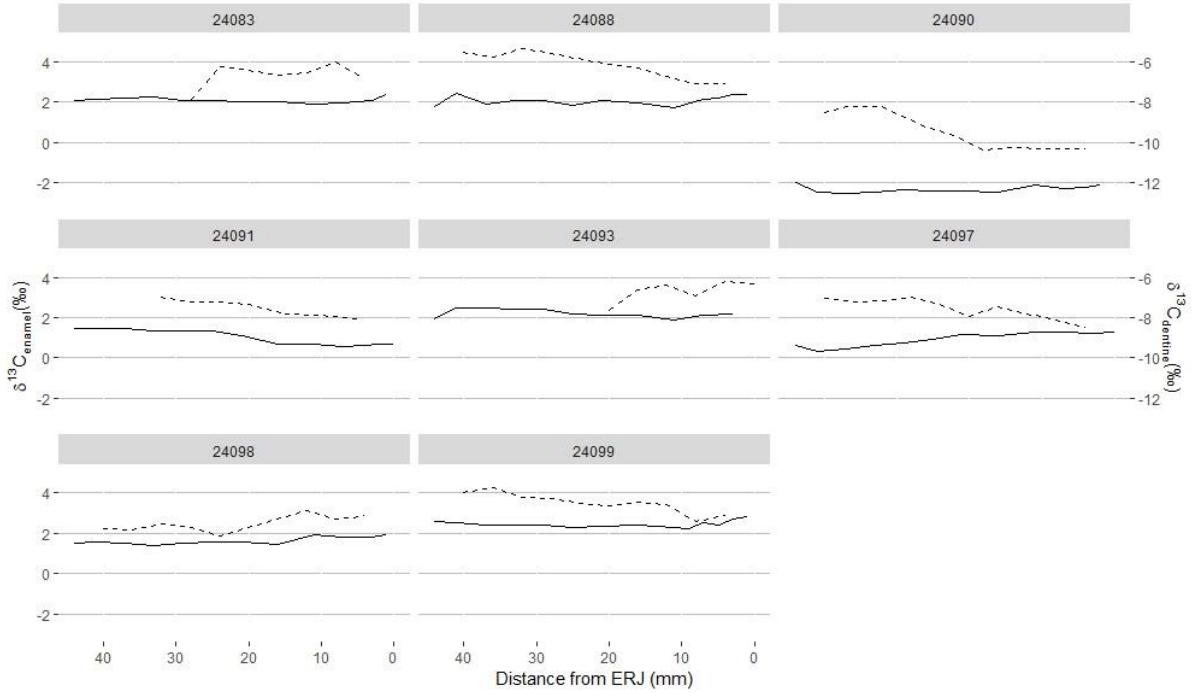


Figure 6.10: Group 2 serial samples. Low amplitude variation in enamel (<1‰) and high amplitude (>1‰) in dentine

Note that the closer the $\delta^{13}C_{enamel}$ and $\delta^{13}C_{dentine}$ lines are to each other, the higher the $\Delta^{13}C_{enamel\text{-}dentine}$.

Dashed line represents dentine, solid line represents enamel.

Figure 6.10 illustrates the $\delta^{13}C_{enamel}$ and $\delta^{13}C_{dentine}$ values for eight individuals which display within-tooth variation, here designated Group 2. This group also contains individuals whose diet was dominated by C_4 grass ($\delta^{13}C_{enamel}$ > 0‰ and $\delta^{13}C_{dentine}$ > -8‰), but greater within-tooth variation in $\delta^{13}C_{dentine}$ values indicate the incorporation of slightly more browse at certain times of the year .The difference between the amplitudes of $\delta^{13}C_{enamel}$ and $\delta^{13}C_{dentine}$ is statistically significant (Mann Whitney-U test, p=0.0009) and depending on whether one tracks $\delta^{13}C_{enamel}$ or $\delta^{13}C_{dentine}$, one gets a different picture of what that animal consumed.

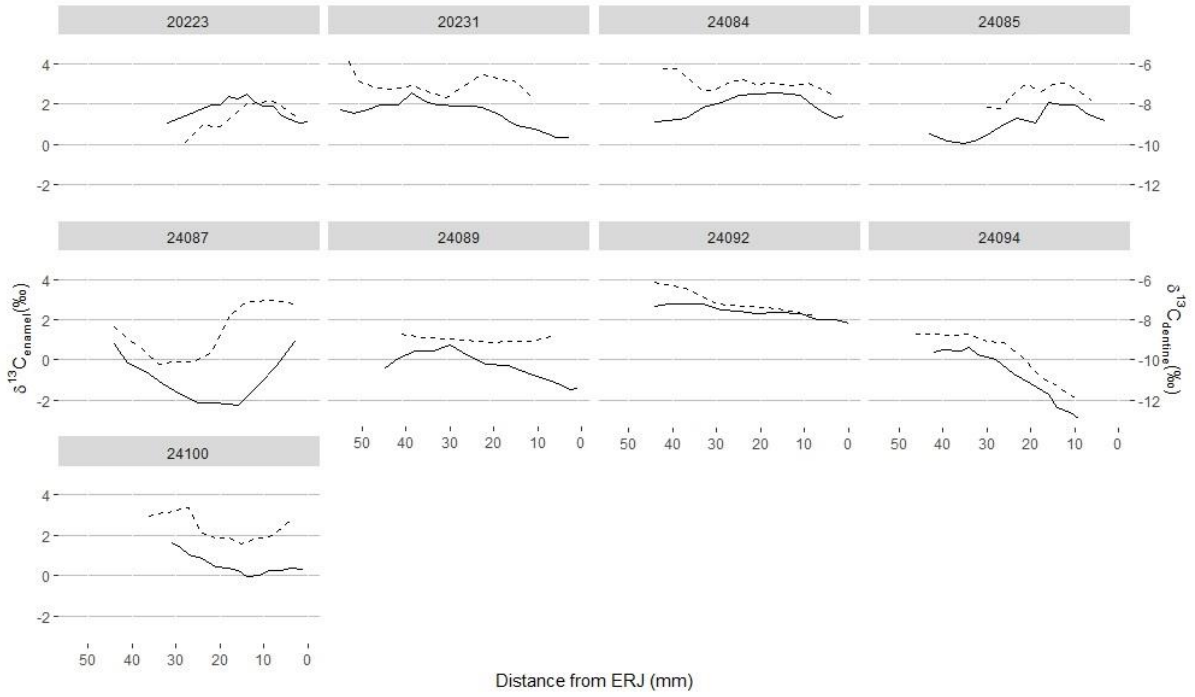


Figure 6.11: Group 3 serial samples. High amplitude variation in both enamel (>1‰) and dentine (>1‰)

Note that the closer the $\delta^{13}C_{enamel}$ and $\delta^{13}C_{dentine}$ lines are to each other, the higher the $\Delta^{13}C_{enamel\text{-}dentine}$.

Dashed line represents dentine, solid line represents enamel.

Figure 6.11 illustrates the $\delta^{13}C_{enamel}$ and $\delta^{13}C_{dentine}$ values for nine individuals which display within-tooth variation, here designated Group 3. In most cases, the fluctuations appear to reflect seasonal shifts. In most instances, the $\delta^{13}C_{enamel}$ and $\delta^{13}C_{dentine}$ profiles show similar trends: when $\delta^{13}C_{dentine}$ increases, so does $\delta^{13}C_{enamel}$ (eg. 20223, 24085 and 24087), giving rise to the non-significant difference between the amplitudes of $\delta^{13}C_{enamel}$ and $\delta^{13}C_{dentine}$ for the group as a whole (Mann Whitney-U test, $p>0.05$). However, in some instances, a change in diet is indicated by $\delta^{13}C_{dentine}$ but not $\delta^{13}C_{enamel}$ (eg 20231). In one case (24084), $\delta^{13}C_{dentine}$ and $\delta^{13}C_{enamel}$ were initially different (at the occlusal surface of the tooth) but became relatively similar as the tooth developed.

Table 6.8: Means and standard deviations of $\delta^{13}C$ values for groups shown in Figures 6.9-6.11

	Group 1 (n=5)	Group 2 (n=8)	Group 3 (n=9)
$\delta^{13}C_{enamel}$ amplitude per tooth (‰)	0.71 ± 0.29	0.70 ± 0.17	2.10 ± 0.83
$\delta^{13}C_{enamel}$ mean of all samples (‰)	1.96 ± 0.68	1.29 ± 1.46	0.85 ± 1.32
$\delta^{13}C_{dentine}$ amplitude per tooth (‰)	0.60 ± 0.21	1.60 ± 0.36	2.00 ± 0.93
$\delta^{13}C_{dentine}$ mean of all samples (‰)	-6.73 ± 0.41	-7.25 ± 1.16	-8.00 ± 1.22
$\Delta^{13}C_{enamel\text{-}dentine}$ amplitude per tooth (‰)	0.10 ± 0.27	-0.91 ± 0.39	0.10 ± 0.80
$\Delta^{13}C_{enamel\text{-}dentine}$ mean of all teeth (‰)	8.76 ± 0.46	8.50± 0.59	8.80 ± 0.78

The amplitude of variation in $\delta^{13}C_{enamel}$ is highest in Group 3, significantly different from Groups 1 and 2 (Mann-Whitney U test, $p = 0.003$ and 0.004 respectively). This is not surprising, since amplitude of variation in $\delta^{13}C_{enamel}$ was one of the criteria for defining the groups. The second criterion was amplitude of variation in $\delta^{13}C_{dentine}$, but this does not differ significantly between the three groups (Table 6.8, Mann-Whitney-U Test, $p > 0.05$). The inference is that $\delta^{13}C_{dentine}$ is more variable than $\delta^{13}C_{enamel}$.

The distribution of mean $\delta^{13}C$ values (both $\delta^{13}C_{enamel}$ and $\delta^{13}C_{dentine}$) do not differ significantly between Groups 1 and 2 (Mann- Whitney U test, $p > 0.05$ for $\delta^{13}C_{enamel}$ and $\delta^{13}C_{dentine}$) but $\delta^{13}C_{enamel}$ and $\delta^{13}C_{dentine}$ in Group 3 are different (more negative) than Groups 1 and 2. In other words, cattle in Group 3 browsed more than those in Groups 1 and 2, leading to the greater amplitude of variation seen in $\delta^{13}C_{enamel}$. The statistical comparisons that are possible here are constrained by small sample sizes, but regardless of how one groups them, there are cattle with low amplitudes of variation in $\delta^{13}C_{enamel}$ but high amplitudes in $\delta^{13}C_{dentine}$. Since variation from a purely C_4 signal derives from the incorporation of varying amounts of browse, the inference is that small quantities of browse are reflected in dentine to a greater extent than in enamel. These differences are very small, however.

6.5 $\delta^{18}O_{enamel}$ values

The $\delta^{18}O$ values for all 273 serial samples analysed are tabled in Appendix 3. They range from -4.7‰ to 3.3‰ with a mean of -0.77 ± 1.44‰. Note that three teeth (24096, 24101 and 24102) have been removed from the dataset as the reproducibility of the oxygen standards for this run was >0.2‰ due to mechanical issues with the mass spectrometer at the time. 10 individuals show a range of variation in $\delta^{18}O$ of less than 2‰. The maximum range of variation within one individual is 4.7‰ (UCT 24095, Figure 6.12). Table 6.9 shows the summary data for the $\delta^{18}O$ values.

Table 6.9: Summary $\delta^{18}O_{enamel}$ values per tooth

Tooth Number	$\delta^{18}O_{enamel}$ (‰)			
	Maximum	Minimum	Mean	Amplitude
20217	-0.2	-2.0	-1.25	1.8
20218	-0.8	-2.8	-1.77	2.0
20220	-1.6	-4.2	-3.03	2.6
20223	-1.2	-4.1	-3.24	2.9
20226	2.0	-0.7	0.74	2.7
20228	1.4	-2.0	-0.04	3.4
20231	-0.4	-2.3	-1.60	1.9
24083	0.8	-1.6	-0.50	2.4
24084	0.3	-0.3	-0.03	0.6
24085	0.2	-0.4	-0.09	0.6
24086	0.1	-0.5	-0.18	0.6
24087	0.0	-0.5	-0.19	0.5
24088	-0.1	-0.6	-0.28	0.5
24089	-0.1	-3.9	-1.40	3.8
24090	-1.4	2.4	0.91	3.8
24091	2.2	-0.6	0.70	2.8
24092	0.3	-2.8	-0.66	3.1
24093	-0.7	-4.7	-2.68	4.0
24094	0.9	-2.0	-0.30	2.9
24095	0.6	-4.1	-1.55	4.7
24096	N/A	N/A	N/A	N/A
24097	-0.3	-3.8	-1.4	3.5
24098	3.3	-3.5	1.56	6.8
24099	2.3	-1.6	0.09	3.9
24100	0.8	-1.8	-0.55	2.6
24101	N/A	N/A	N/A	N/A
24102	N/A	N/A	N/A	N/A

There is no clustering of individuals dating to AD1300-1400 (20228, 20231, 24083, 24084, 24085, 24086, 24087, 24088, 24092, 24093, 24094, 24095, 24098, 24099, 24100) compared with those dating to AD1400-1600 (20217, 20218, 20220, 20223, 20226, 24092). UCT 24100 (dating to AD250-400) fall within the same range the other individuals (Figure 6.12)

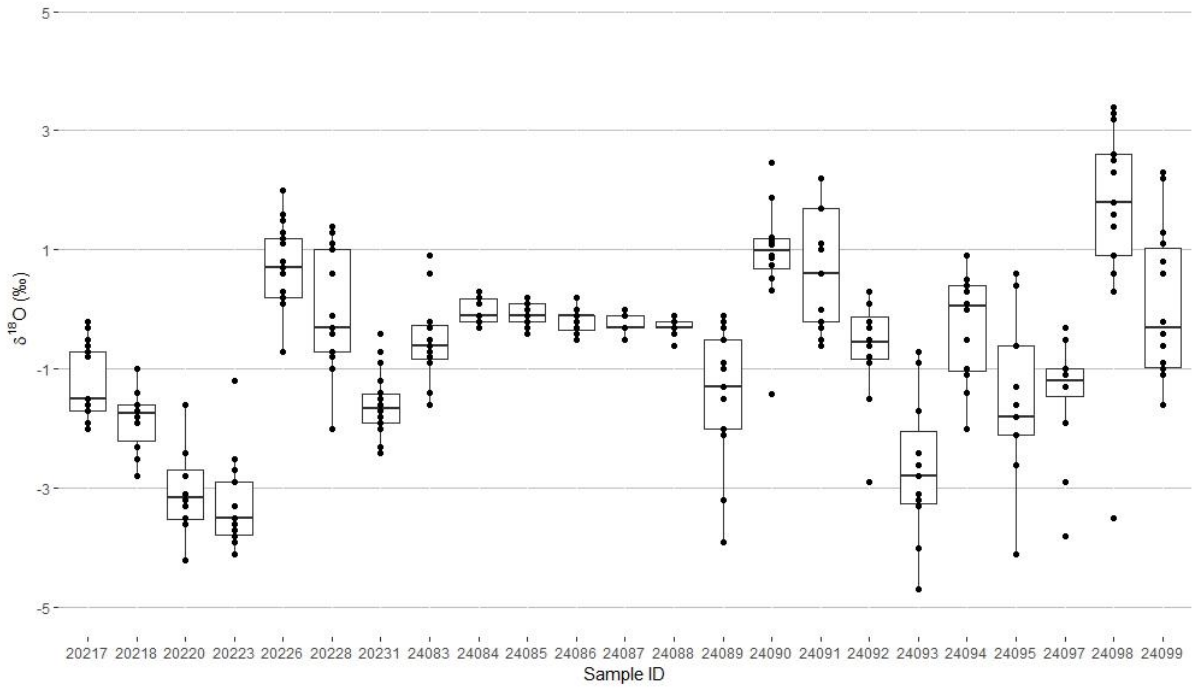


Figure 6.12: Box plot of $\delta^{18}O_{enamel}$ values

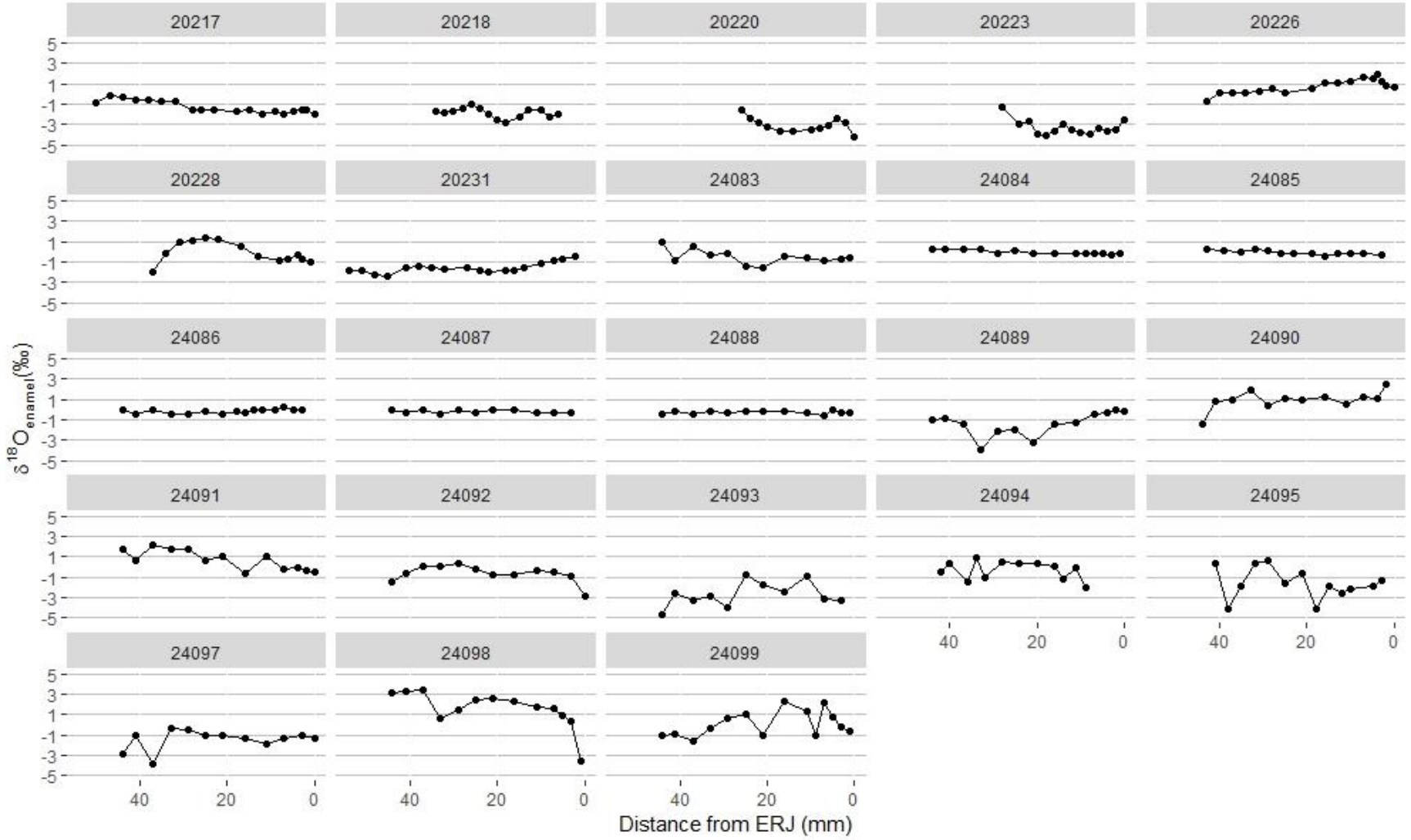


Figure 6.13: $\delta^{18}O_{enamel}$ values for 20 archaeological teeth. Point 'zero' on the x-axis indicates the position of the ERJ.

Five specimens show consistent $\delta^{18}O$ values down the height of the crown (Figure 6.13 24084, 24085, 24086, 24087 and 24088) with amplitudes less than 0.7‰. Other individuals show a greater degree of seasonal variation (Figure 6.13 20223, 20226, 20228, 20220, 24092 and 24098) with amplitudes between 2.6 and 6.8‰. The remainder of the specimens (Figure 6.14 20218, 20231, 24083, 24093, 24094, 24095, 24099 and 24100) show rapidly fluctuating $\delta^{18}O$ values with amplitudes between 2‰ and 4‰. Overall, there is considerable inter-individual variation in the $\delta^{18}O$ profiles.

6.6 $\delta^{15}N_{dentine}$ values

$\delta^{15}N$ values for all serial samples are tabled in Appendices 3 and 4. Table 6.10 presents data from the three modern cattle teeth, which have $\delta^{15}N$ values that range between 8.7 and 9.8‰. Their amplitudes fall between 2.4‰ and 3.3‰.

Table 6.10: Summary $\delta^{15}N_{dentine}$ values for modern teeth

Tooth Number	$\delta^{15}N_{dentine}$ (‰)						
	Maximum	Minimum	Mean	Amplitude	Mean %C	Mean %N	C:N ratio
24142	9.8	6.5	7.51	3.3	44.0	14.9	3.4
24143	9.5	6.4	8.28	3.1	39.6	14.7	3.2
24144	8.7	6.3	7.14	2.4	43.7	14.5	3.4

$\delta^{15}N_{dentine}$ values for the serial samples of the archaeological teeth fall between 3 and 8‰ except for specimen 24085 which includes two values of 8.9‰ and 10.3‰ (Table 6.11). The lowest values are from specimen 20231.

Table 6.11: Summary $\delta^{15}N_{dentine}$ values for archaeological teeth

Tooth Number	$\delta^{15}N_{dentine}$ (‰)						
	Maximum	Minimum	Mean	Amplitude	Mean %C	Mean %N	C:N ratio
20217	7.1	6.2	6.73	0.9	40.8	13.6	3.3
20218	6.8	6.2	6.48	0.6	38.5	13.7	3.3
20220	7.1	6.0	6.37	1.1	37.4	13.1	3.3
20223	5.7	5.1	5.49	0.6	29.1	11.6	3.4
20226	5.3	4.6	4.79	0.7	37.3	12.5	3.5
20228	7.0	5.5	6.24	1.5	44.1	15.9	3.2
20231	4.7	2.8	3.68	1.8	37.5	13.3	3.3
24083	5.7	4.8	5.15	0.9	34.7	11.5	3.3
24084	5.2	3.4	4.00	1.8	37.0	12.8	3.4
24085	10.3	5.5	7.17	4.8	35.9	12.8	3.3
24086	5.4	4.5	4.80	0.9	39.7	14.5	3.2
24087	5.2	4.3	4.81	0.9	33.6	11.5	3.4
24088	6.2	5.4	5.70	0.8	35.9	13.7	3.3
24089	6.3	5.3	5.87	1.0	39.4	14.1	3.3
24090	8.1	7.0	7.46	1.1	39.3	14.3	3.2
24091	5.2	4.8	4.96	0.4	38.2	13.3	3.3
24092	6.0	5.1	5.56	0.9	40.5	14.7	3.2
24093	6.0	4.3	5.43	1.7	43.7	15.7	3.3
24094	6.9	6.4	6.66	0.5	35.7	12.7	3.3
24095	6.1	5.2	5.77	0.9	35.7	14.1	3.0
24096	7.1	4.8	6.16	2.3	35.9	12.1	3.5
24097	6.4	4.2	5.59	2.2	36.0	12.9	3.3
24098	6.1	4.6	5.09	1.6	37.0	13.5	3.3
24099	4.8	4.4	4.56	0.5	36.4	12.7	3.3
24100	7.2	4.1	4.98	3.1	39.7	14.4	3.2
24101	6.4	4.0	5.18	2.5	43.7	15.7	3.2
24102	6.9	5.9	6.50	1.0	42.1	15.2	3.2

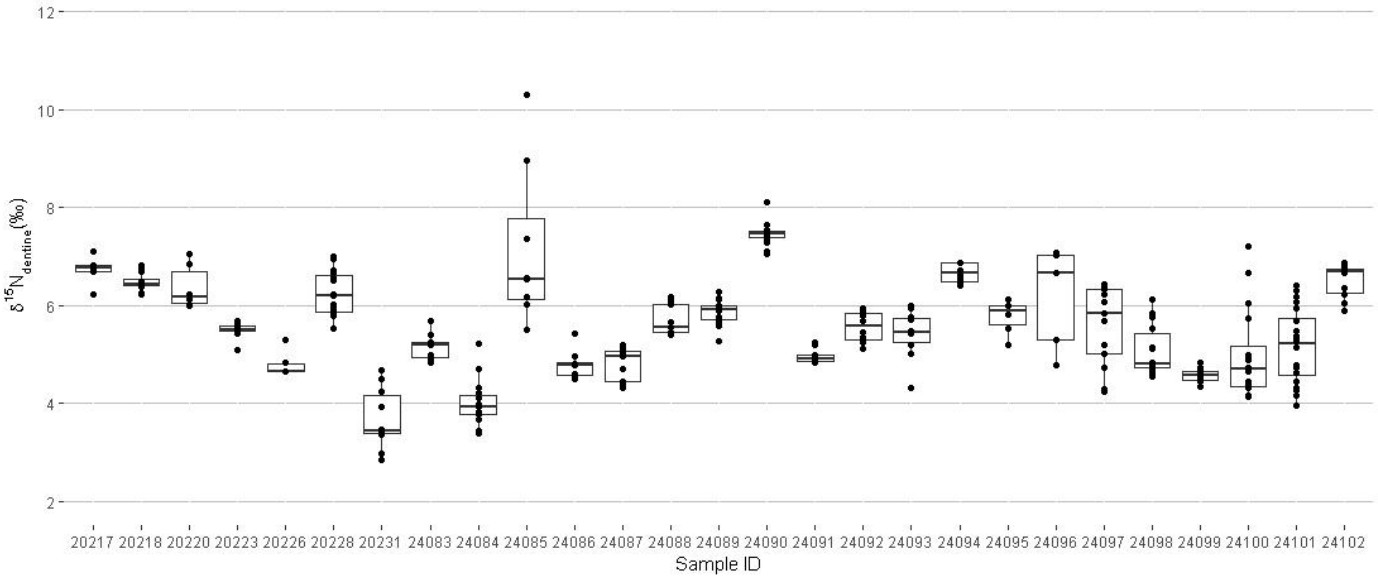


Figure 6.14: Boxplot of $\delta^{15}N_{dentine}$ values per tooth

The $\delta^{15}N$ values for the three modern teeth are, on average, more positive than those for the archaeological specimens (Figure 6.15). The amplitudes of variation in the modern samples are higher than in the archaeological teeth. This could be due to varying $\delta^{15}N$ values in the soil substrates or the drought experienced by the region in the last few years.

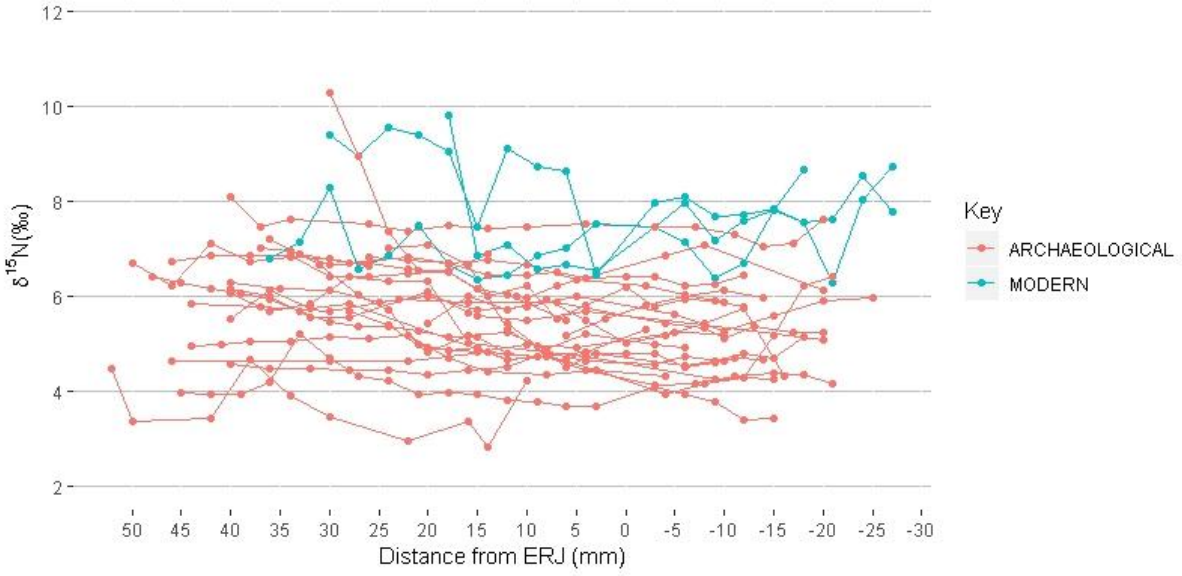


Figure 6.15: $\delta^{15}N_{dentine}$ values for 27 archaeological and 3 modern teeth. Point 'zero' on the x-axis indicates the position of the ERJ.

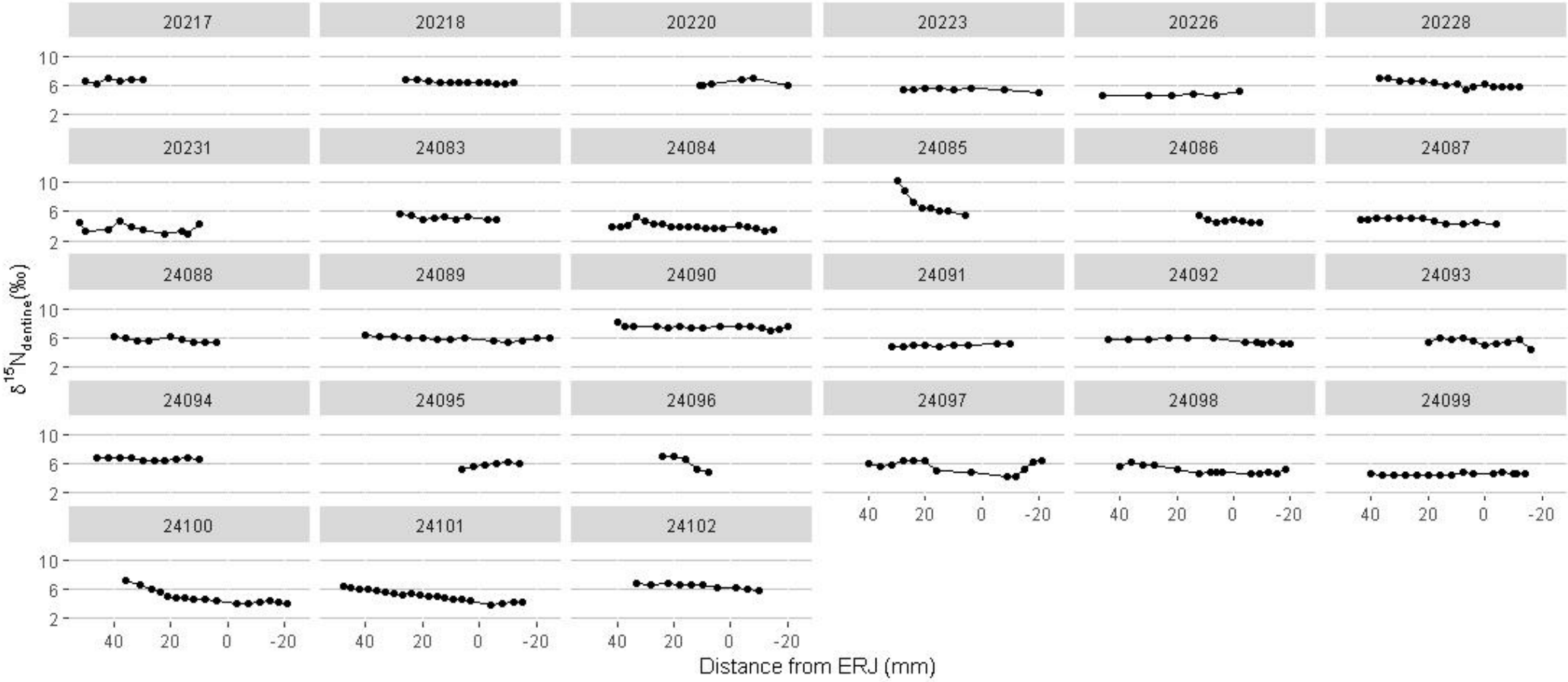


Figure 6.16: $\delta^{15}N_{dentine}$ values for 27 archaeological teeth. Point 'zero' on the x-axis indicates the position of the ERJ.

The $\delta^{15}N$ values for serial samples of archaeological teeth do not change much over the period the teeth grew. 11 teeth contained amplitudes of variation of less than 1‰ (Figure 6.16. 20217, 20218, 20220, 20223, 20226, 24083, 24087, 24088, 24092, 24094, 24099). 24085 shows an anomalously high amplitude of 4.8‰. The highest value (10.3‰) is at the occlusal end of the tooth, falling to 5.5‰ closer to the ERJ. This may indicate that this individual was born in a drought. Other than 24100 (with an amplitude of 2.6‰) the remainder of the specimens have amplitudes of between 1 and 2.3‰.

6.7 $^{87}Sr/^{86}Sr$ values

35 vegetation samples were collected across the five major geological substrates in southern Zimbabwe, as shown on Figure 6.17. The $^{87}Sr/^{86}Sr$ ratios for each are reported in Table 6.12. The colours used to distinguish the different geological substrates in Figure 6.17 will be used in subsequent figures to identify samples collected on those substrates. Sample numbers 4, 5, 9 and 16 were located on the border of two geologies and therefore it is unclear which geology their strontium ratios reflect. As such, these samples have been excluded from the data analysis.

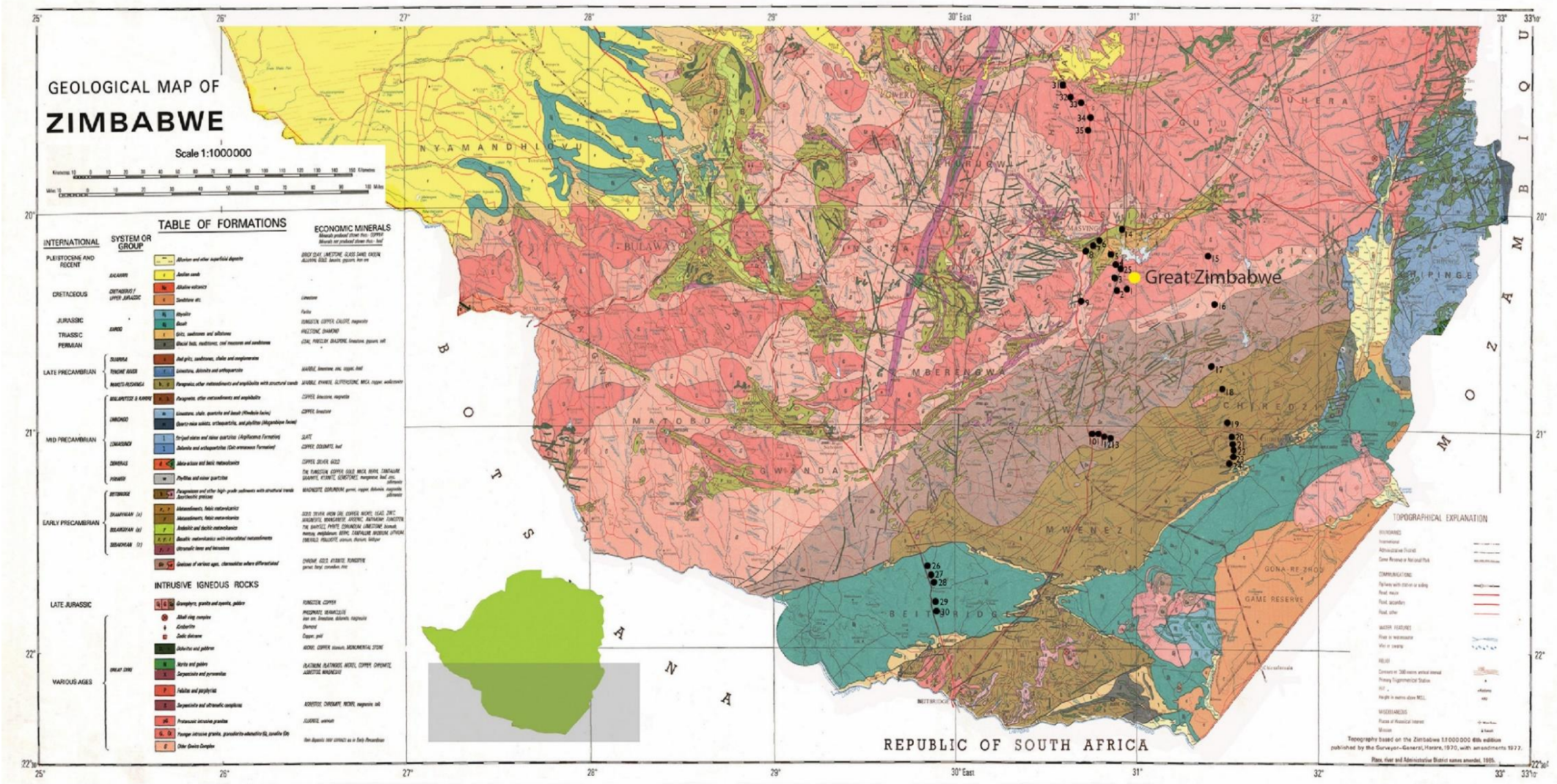


Figure 6.17: Location of vegetation samples from southern Zimbabwe in relation to bedrock geology (Drawn by Neil Rusch)

Table 6.12: $^{87}Sr/^{86}Sr$ ratios for modern vegetation samples collected in southern Zimbabwe

Geology	Sample number	Colour on geology map	$^{87}Sr/^{86}Sr$
Karoo Basalt	26	Blue	0.7054
Karoo Basalt	27	Blue	0.7060
Karoo Basalt	28	Blue	0.7072
Karoo Basalt	29	Blue	0.7063
Karoo Basalt	30	Blue	0.7067
Gneisses of various ages	10	Grey	0.7232
Gneisses of various ages	17	Grey	0.7238
Gneisses of various ages	11	Grey	0.7244
Gneisses of various ages	12	Grey	0.7370
Gneisses of various ages	13	Grey	0.7480
Basaltic metavolcanics	8	Light Green	0.7236
Basaltic metavolcanics	7	Light Green	0.7238
Basaltic metavolcanics	14	Light Green	0.7241
Basaltic metavolcanics	6	Light Green	0.7250
Paragneisses. other metasediments and amphibolite	19	Olive Green	0.7157
Paragneisses. other metasediments and amphibolite	23	Olive Green	0.7172
Paragneisses. other metasediments and amphibolite	20	Olive Green	0.7321
Paragneisses. other metasediments and amphibolite	21	Olive Green	0.7339
Paragneisses. other metasediments and amphibolite	18	Olive Green	0.7349
Paragneisses. other metasediments and amphibolite	22	Olive Green	0.7375
Paragneisses. other metasediments and amphibolite	24	Olive Green	0.7408
Younger Intrusive Granite	25	Pink	0.7552
Younger Intrusive Granite	2	Pink	0.7746
Younger Intrusive Granite	1	Pink	0.7827
Younger Intrusive Granite	34	Pink	0.7850
Younger Intrusive Granite	3	Pink	0.7879
Younger Intrusive Granite	35	Pink	0.7906
Younger Intrusive Granite	33	Pink	0.8092
Younger Intrusive Granite	32	Pink	0.8282
Younger Intrusive Granite	31	Pink	0.8781

As shown in Table 6.12. five samples were taken from the 'Karoo Basalt' rock formations. Their $^{87}Sr/^{86}Sr$ values range from 0.7054 to 0.7067. Five samples were taken from the 'Gneisses of various ages' formations and their values range from 0.7232 to 0.7480. Four samples were taken from the 'Basaltic metavolcanics' baserocks with $^{87}Sr/^{86}Sr$ ranging from 0.7236 to 0.7249. Seven samples were taken from the 'Paragneisses, other metasediments and amphibolites' formations with $^{87}Sr/^{86}Sr$ ranging from 0.7156 to 0.7407. A total of 10 samples were taken from the 'Younger intrusive granites' and their $^{87}Sr/^{86}Sr$ ratios had the largest range of 0.7552 to 0.8780. Figure 6.18 shows the distribution of these values.

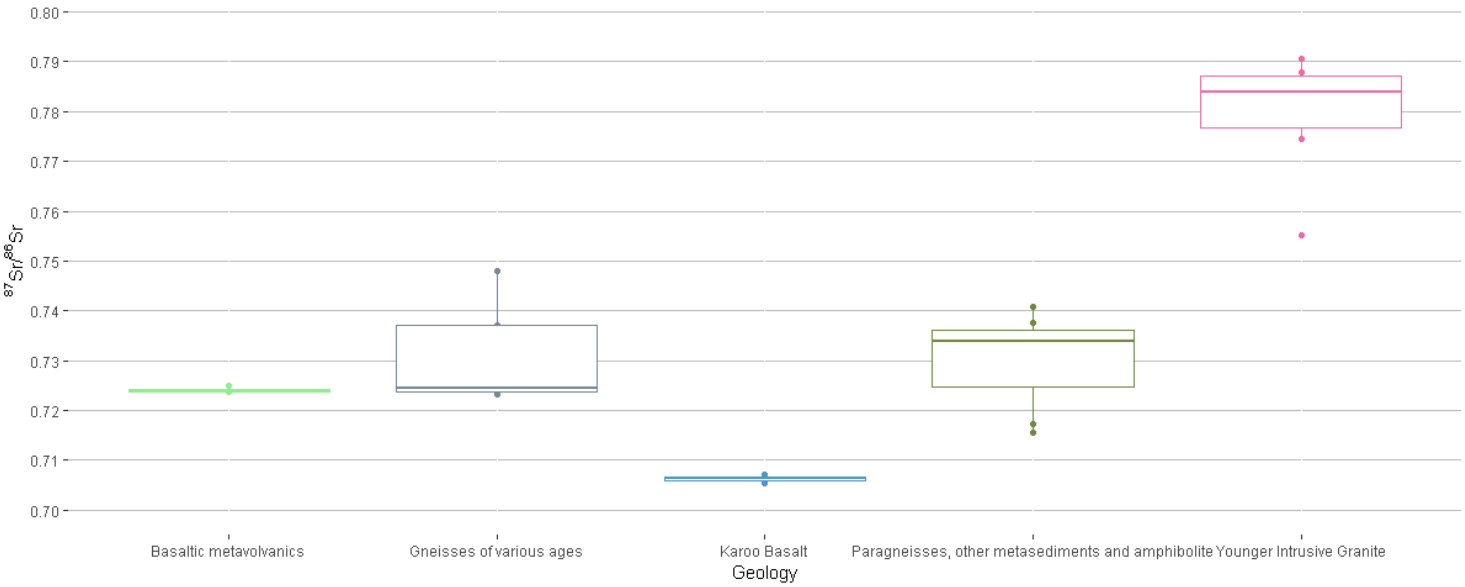


Figure 6.18: Boxplot showing $^{87}Sr/^{86}Sr$ of plants from different bedrock geologies

A total of 588 $^{87}Sr/^{86}Sr$ values were measured up the heights of the tooth crowns of all 27 archaeological teeth. All values are tabled in Appendix 3, and the summary data is in Table 6.13. The maximum $^{87}Sr/^{86}Sr$ value was 0.7892 and the minimum 0.7138. The largest within-tooth amplitude was 0.0221 (for specimen 24089); the remaining specimens showed amplitudes of less than 0.0169.

Table 6.13: Summary $^{87}Sr/^{86}Sr$ for 27 archaeological teeth

Tooth Number	$^{87}Sr/^{86}Sr$			
	Maximum	Minimum	Mean	Amplitude
20217	0.7410	0.7285	0.7355	0.0125
20218	0.7361	0.7287	0.7316	0.0074
20220	0.7702	0.7650	0.7679	0.0052
20223	0.7892	0.7853	0.7880	0.0039
20226	0.7510	0.7396	0.7455	0.0114
20228	0.7446	0.7314	0.7358	0.0132
20231	0.7562	0.7415	0.7499	0.0147
24083	0.7305	0.7224	0.7245	0.0080
24084	0.7479	0.7361	0.7391	0.0117
24085	0.7350	0.7297	0.7329	0.0053
24086	0.7882	0.7714	0.7838	0.0169
24087	0.7359	0.7325	0.7347	0.0034
24088	0.7370	0.7224	0.7276	0.0146
24089	0.7527	0.7306	0.7331	0.0221
24090	0.7447	0.7329	0.7360	0.0118
24091	0.7253	0.7138	0.7213	0.0115
24092	0.7341	0.7245	0.7281	0.0096
24093	0.7528	0.7323	0.7431	0.0206
24094	0.7479	0.7406	0.7434	0.0073
24095	0.7381	0.7266	0.7320	0.0114
24096	0.7405	0.7303	0.7337	0.0102
24097	0.7326	0.7282	0.7298	0.0043
24098	0.7582	0.7338	0.7338	0.0244
24099	0.7395	0.7346	0.7367	0.0049
24100	0.7480	0.7411	0.7446	0.0069
24101	0.7303	0.7168	0.7234	0.0136
24102	0.7312	0.7267	0.7281	0.0045

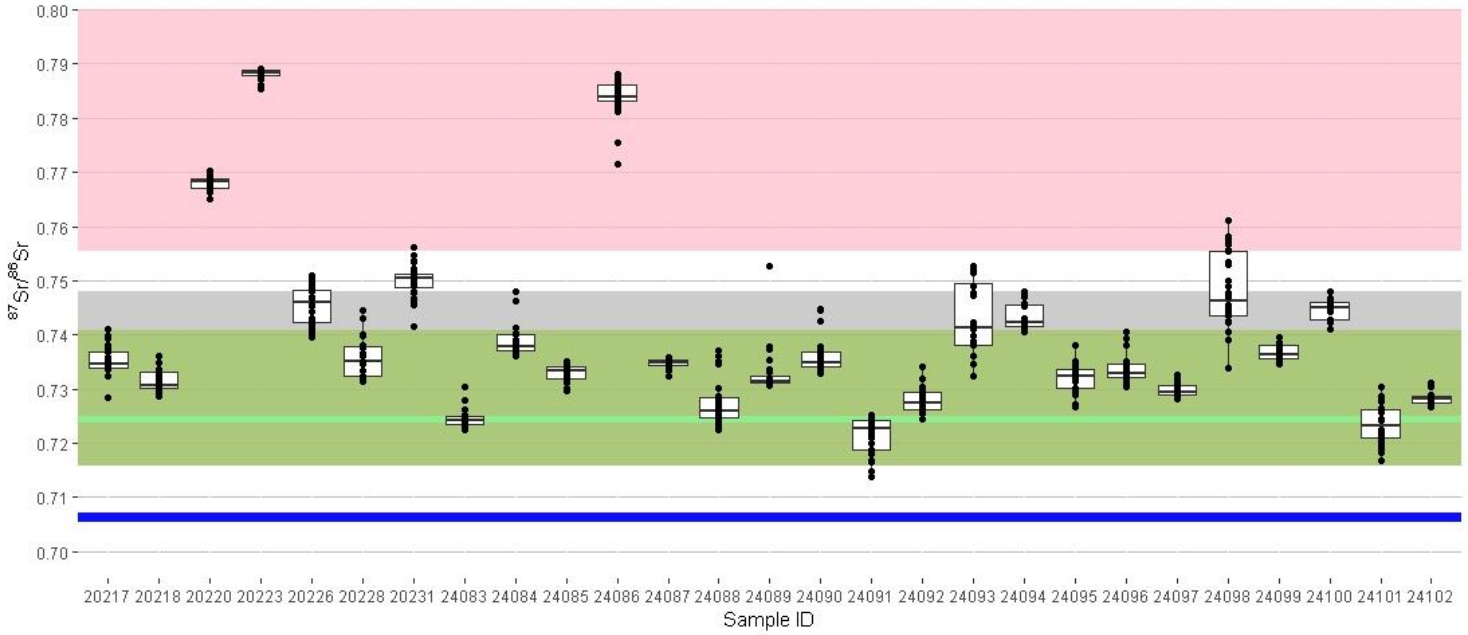


Figure 6.19: Boxplot of $^{87}Sr/^{86}Sr$ for each tooth

Coloured boxes show the ratios associated with each bedrock geology according to colours in Table 6.12. Pink box is geologically local to Great Zimbabwe. other coloured boxes are geologically non-local to Great Zimbabwe.

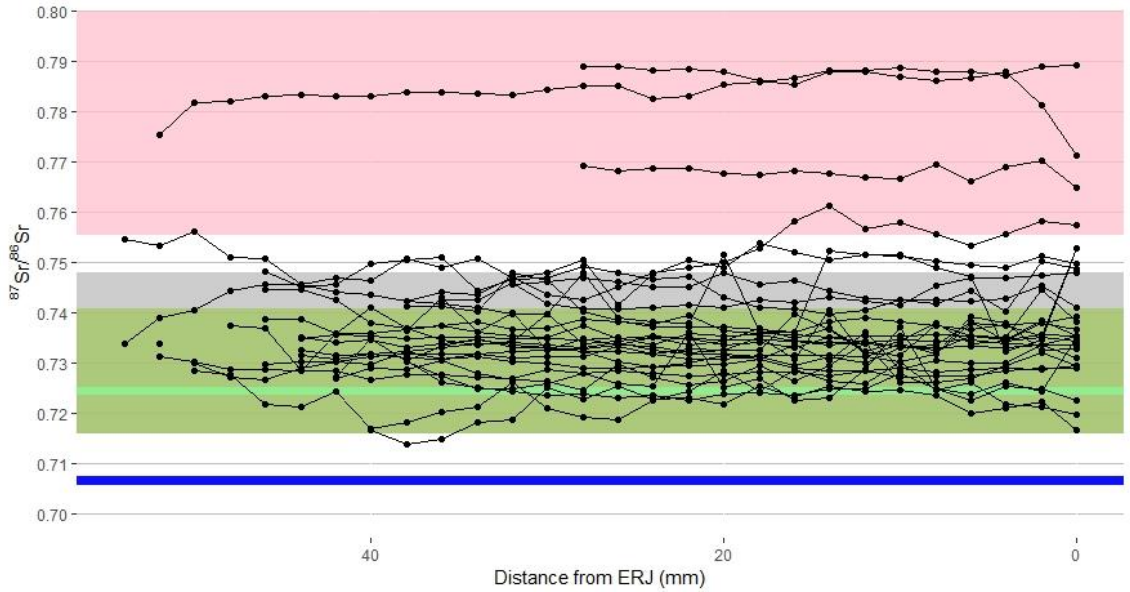


Figure 6.20: Serial $^{87}Sr/^{86}Sr$ for 27 archaeological teeth. Point 'zero' on the x-axis indicates the position of the ERJ.

Coloured boxes show the ratios associated with each bedrock geology according to colours in Table 6.12. Pink box is local to Great Zimbabwe. other coloured boxes are non-local to Great Zimbabwe.

Three specimens (20220, 20223 and 24086) have $^{87}Sr/^{86}Sr$ consistent with the geology local to Great Zimbabwe throughout the one-year period of tooth formation (Figure 6.20 pink box, values greater than 0.7552). 21 specimens have $^{87}Sr/^{86}Sr$ values which are consistent with the geology non-local to Great Zimbabwe throughout the one-year period of tooth formation (Figure 6.20 light green, olive green and grey boxes, values between 0.7156 and 0.7480). Three specimens (24093, 24098 and 20231) show $^{87}Sr/^{86}Sr$ values consistent with the geology non-local to Great Zimbabwe at some portion of the tooth (values <0.745) and then change to local values in another portion (values >0.757) None of the specimens show $^{87}Sr/^{86}Sr$ in the range of the basalt geology (blue box) at any point.

6.8 Summary

On comparing archaeological teeth with specimens from museum collections, it was found that mandibular second molars from cattle can be distinguished from those of buffalo based on length and breadth. There is some overlap in the dimensions of maxillary teeth but given the overwhelming dominance of cattle compared with wild fauna at Great Zimbabwe, the teeth analysed in this study can confidently be assigned to cattle. Both $\delta^{13}C_{enamel}$ and $\delta^{13}C_{dentine}$ values showed that the animals' diets consisted largely of C_4 graze. In some instances, C_3 browse showed more clearly in dentine than enamel. In most teeth, $\delta^{18}O$ and $\delta^{15}N$ values varied relatively little over the period of tooth formation, although there were some exceptions. $\delta^{15}N$ values of modern teeth were higher than those of archaeological teeth. The majority of $^{87}Sr/^{86}Sr$ values were consistent with geologies non-local to Great Zimbabwe. Only three specimens showed $^{87}Sr/^{86}Sr$ in all serial samples consistent with the geology local to Great Zimbabwe, while three spanned local/non-local values.

The next chapter discusses the implications of the results in a wider archaeological context.

7.1 Introduction

This study aimed to use multiple stable and radiogenic isotopes to understand more about the herd management and procurement strategies of the cattle supplied to Great Zimbabwe. This section explores why (in some cases) differences were observed between the stable carbon isotope profiles of enamel and dentine from the same animal. It then discusses the stable and radiogenic isotope results in light of the research aims and objectives outlined in Chapter 1. Next, the limitations of this study are outlined and some suggestions made for future work. Finally, there is a brief statement of the main conclusions reached.

7.2 Interpreting the observed differences between $\delta^{13}C_{enamel}$ and $\delta^{13}C_{dentine}$ profiles

One somewhat surprising finding of this study was that $\delta^{13}C_{enamel}$ and $\delta^{13}C_{dentine}$ profiles up the crowns of the same teeth did not always show the same patterns. What might account for this? One consideration is that the dentine and enamel samples analysed in this study probably incorporate different degrees of time-averaging. Zazzo et al. (2006) reported that in cattle, horizontal slices of dentine 2 mm thick reflected diet over a period of approximately four months. The slices analysed here were 2-3 mm thick, averaging four to six months. This is similar to, but not quite as long as the 6-7 months associated with 4mm-thick horizontal samples of tooth enamel (Balasse, 2002; Zazzo et al., 2005). Seasonal variations in diet, such as greater intake of browse during the dry season, might therefore be expected to show up in dentine more strongly than in enamel.

A second possibility is dietary routing. Browse usually contains a higher proportion of protein than graze, although secondary chemicals can inhibit absorption (Codron et al., 2007). In a study of wild ungulates in the Kruger Park, South Africa, Codron et al. (2007) found that faecal %N (a proxy for dietary protein) was negatively correlated with percentage of grass in the diet. We assume that the trends will be the same for nitrogen (protein) that is absorbed, rather than excreted. Cattle eating browse will therefore have higher-protein diets than those eating only graze. Since dietary protein is preferentially

routed to the consumer's protein tissues (Ambrose and Norr, 1993; Tieszen and Fagre, 1993; Howland et al., 2003; Jim et al., 2004;), browse should reflect more strongly in dentine than enamel.

Codron et al. (2012) reported $\delta^{13}C_{carbonate}$ and $\delta^{13}C_{collagen}$ in serial samples of ivory (dentine) from large elephant tusks from the Kruger Park. Dentine powder was drilled from a series of growth increments and some powders divided into two for measurement of $\delta^{13}C_{carbonate}$ and $\delta^{13}C_{collagen}$ respectively. The carbonate and collagen profiles are, therefore, more closely time-matched than in this study. These authors, too, found less variation in $\delta^{13}C_{carbonate}$ than $\delta^{13}C_{collagen}$, and attributed the difference to dietary routing,

Variation of up to 5‰ in $\Delta^{13}C_{collagen\text{-}carbonate}$ has previously been reported among different herbivore species (Codron et al., 2018) (although collagen and carbonate were not necessarily measured on the same individual). We find differences of up to 3.2‰ between different individuals of a single species. We also find that $\Delta^{13}C_{collagen\text{-}carbonate}$ can vary along the growth axis of a single tooth. Such variation may be particularly evident in these cattle due to their isotopically heterogeneous diets (C_4 graze in addition to C_3 browse).

Cattle excrete a significant proportion (5-10%) of ingested carbon as methane (Johnson and Ward, 1996; Lassey et al., 1997). Methanogenesis in the gut enriches blood bicarbonate in ^{13}C, thereby raising $\delta^{13}C_{enamel}$ (Cerling and Harris 1999; Hedges 2003) and further increasing the difference between $\delta^{13}C_{enamel}$ and $\delta^{13}C_{dentine}$. Codron et al. (2018) argue that this effect is greater in grazers than browsers, since secondary chemicals in browse can inhibit methane production. In this study, we do not see significant differences in $\Delta^{13}C_{enamel\text{-}dentine}$ between Groups 1, 2 and 3, but since all the animals studied here were principally grazers, this effect may be too subtle to detect.

In sum, the results show a median $\Delta^{13}C_{\ enamel\text{-}dentine}$ per tooth of 8.7‰ (range 7.3-10.5‰). Similar ranges (>3‰) have previously been considered to indicate trophic level or species differences but are seen here within a single herbivorous species (*Bos taurus*). The mean $\delta^{13}C_{enamel}$ and $\delta^{13}C_{dentine}$ values per tooth are strongly correlated ($R^2 = 0.9$). In some cases, $\delta^{13}C_{dentine}$ values provide a more sensitive record than $\delta^{13}C_{enamel}$ of the ingestion of small quantities of browse. Our results agree with the hypothesis of Codron et al. (2018), that browsing and grazing affect $\delta^{13}C_{carbonate}$ and $\delta^{13}C_{collagen}$ differently. $\delta^{13}C$ profiles based on serial samples are directly comparable only if they derive from the same tissue.

7.3 Assessing heterogeneity and procurement of cattle supplied to Great Zimbabwe

The serially sampled cattle teeth show a surprising amount of heterogeneity in both diets and areas of origin. $^{87}Sr/^{86}Sr$ measurements enable the teeth (i.e. cattle) to be divided into those that may have been local and those that were non-local to Great Zimbabwe. A few animals fall into an intermediate category. Even within these groups, stable isotope ratios reflect dietary and environmental heterogeneity. If there is a 14‰ spacing between a 100% C_4 grazing diet and a 100% C_3 browsing diet, one can estimate the amounts of graze and browse in the animal's diet over the period of tooth growth. With this information, one can broadly categorise the degree of dietary change over the period of tooth growth.

Three individuals show $^{87}Sr/^{86}Sr$ consistent with the geological substrates around Great Zimbabwe. These are UCT20220, UCT20223 and UCT24086. The radiocarbon ages of UCT20220 and UCT20223 calibrate to AD1400-1600, while UCT24086 calibrates to AD1300-1400. The (more recent) UCT20220 and UCT20223 have low $\delta^{18}O$ values (means of -3.03‰ and -3.24‰ respectively) indicating a cool, moist environment as might be expected in the cool, high rainfall area of Great Zimbabwe (see Fig. 2.1). These teeth have the lowest $\delta^{18}O$ values of the entire dataset. The older tooth UCT24086 has a higher $\delta^{18}O$ value (mean $\delta^{18}O$= -0.18‰), falling approximately in the middle of the range seen in this study. This probably indicates that it was raised in a different hydrological environment than UCT20220 and UCT20223, or it reflects a dry year. It should be noted that large within-animal ranges in $\delta^{18}O$ (5.3‰ on average) were found in elephants in the Kruger National Park (Codron et al., 2012), but the variation did not appear to be a seasonal effect, nor related to annual rainfall. The authors argue that $\delta^{18}O$ values track shifting environmental conditions during the elephants' lifespans (Codron et al., 2012). The maximum within-tooth variation in $\delta^{18}O$ seen in this study was 6.8‰, although most teeth had much smaller ranges. Ten teeth (more than a third of the sample) showed variation of less than 2‰. It is clearly important to avoid over-interpreting variation in $\delta^{18}O$, but it seems reasonable to infer that the cattle teeth with the highest $^{87}Sr/^{86}Sr$ in combination with the lowest $\delta^{18}O$ values derive from the high-rainfall area of the plateau, i.e. the near vicinity of Great Zimbabwe.

UCT20220 and UCT20223 both consumed diets that consisted mainly of C_4 grass (UCT20220 mean $\delta^{13}C_{enamel}$ = 2.71‰, mean $\delta^{13}C_{dentine}$ = -7.10‰; UCT20223 mean $\delta^{13}C_{enamel}$ = 1.70‰, mean $\delta^{13}C_{dentine}$ = -8.56‰). UCT24086 consumed somewhat less C_4 grass (mean $\delta^{13}C_{enamel}$ = 0.63‰, mean $\delta^{13}C_{dentine}$ = -8.66‰). Although these three individuals were raised on the same geological substrate, they had slightly different diets and environmental conditions. This may be as a result of environmental change over time (perhaps just from year to year), or because they were raised in herds living in different environments.

Three individuals (UCT20231, UCT24093 and UCT24098) show varying $^{87}Sr/^{86}Sr$ consistent with movement between the geological substrates local to Great Zimbabwe, and those approximately 40-120kms south of the site. The radiocarbon ages for UCT20231 and UCT24098 both calibrate to AD1300-1400. UCT24093 was recovered from the same archaeological context, so probably dates to the same time period. UCT24093 had low $\delta^{18}O$ values (mean=-2.67‰), reflecting a cool, moist environment. UCT20231 and UCT24098 had mean $\delta^{18}O$ values of -1.60‰ and 1.56‰ respectively. Both UCT24093 (mean $\delta^{13}C_{enamel}$= 2.21‰, mean $\delta^{13}C_{dentine}$ = -6.82‰) and UCT24098 (mean $\delta^{13}C_{enamel}$=1.60‰, mean $\delta^{13}C_{dentine}$= -7.37‰) showed relatively little variation in diet (~10%) over the period of tooth growth, while UCT20231 showed ~20%, although this individual ate mainly C_4 grass (mean $\delta^{13}C_{enamel}$ = 1.49‰, mean $\delta^{13}C_{dentine}$= -7.07‰). These combined datasets indicate that even though these three animals were moving across geological substrates, they were raised in areas with different moisture regimes and had access to different amounts of C_4 grasses through the period of tooth formation.

$^{87}Sr/^{86}Sr$ values for the remaining 21 individuals are consistent with the geological substrates between 40 and 120kms south of Great Zimbabwe. Even though their $\delta^{18}O$ values are not very different from one another (means range from -1.77‰ to 0.74‰), their $\delta^{13}C$ values show heterogeneity in diet likely resulting from different degrees of consumption of C_4 grasses. Each group will be discussed in turn.

Nine individuals (UCT20217, UCT20218, UCT20226, UCT20228, UCT24088, UCT24091, UCT24095, UCT24096 and UCT24102) show little (<10%) variation in the C_3/C_4 composition of the diet over the period of tooth formation. One tooth (UCT20218) has a radiocarbon age that calibrated to AD1400-1600, whilst the others were either directly radiocarbon dated or recovered in the same context as specimens radiocarbon dated to AD1300-1400.

Three individuals (UCT24084, UCT24087 and UCT24094) show a high range of variation (~20%) in the C_3/C_4 composition of their diets over the period of tooth formation. All three teeth were recovered in the same context as those which were radiocarbon dated to the AD1300-1400 period. They consumed more C_3 browse than the other individuals and as a result, their mean $\delta^{13}C$ values are lower.

Nine individuals (UCT24085, UCT24089, UCT24090 UCT24083, UCT24092, UCT24097, UCT24099, UCT24101and UCT24100) showed moderate variation in diet of between 10-15% over the period of tooth formation. UCT24100 dated to much earlier than the other teeth at AD250-400, while one (UCT24092) calibrated to AD1400-1600. The remaining individuals were recovered in the same context as those which were radiocarbon dated to the AD1300-1400 period. Although UCT24090 showed little variation in diet, it consumed much more C_3 browse than the other individuals ($\delta^{13}C_{dentine}$ range of -12.60‰ to -10.04‰, $\delta^{13}C_{enamel}$ range of -2.5‰ to -2.0‰). This tooth has the most consistently negative $\delta^{13}C_{dentine}$ values in the study. It is clear from the above that the various isotopic indicators do not co-vary. This shows that the cattle came from multiple different herds/environments.

Assuming that cattle included C_3 browse into their diets mainly during the dry winter months, it is possible to identify if more than one birth season is evident in these teeth. Based on the trajectories of serial $\delta^{13}C_{dentine}$ values it is clear that the patterns vary. The $\delta^{13}C_{dentine}$ values for UCT24087 shows a strong decrease in $\delta^{13}C$ values from the occlusal surface towards the ERJ, then an increase. If consuming C_3 browse only occurs in winter, this individual may have been born in late summer/autumn. UCT24086 has a shorter dentine record but also has low $\delta^{13}C_{dentine}$ values in the earlier-forming portion of the tooth then more positive values closer to the ERJ, leading to the same conclusion. UCT24085 and UCT20223 show an increase in $\delta^{13}C_{dentine}$ values followed by consistently high values. These individuals may have been born in a different season, possibly early summer. The teeth with flat $\delta^{13}C_{dentine}$ profiles do not show any seasonality and therefore cannot reveal birth seasons. The $\delta^{18}O_{enamel}$ values did not show any seasonal trajectory in any of the teeth. Balasse (2002) has shown that due to the delay in maturation and the complex mineralisation fronts which occur during the tooth growth process, determining the season of birth is complicated. In this dataset however, we do not aim to identify the birth season (ie. summer or spring), but it is evident that the $\delta^{13}C_{dentine}$ trajectories are

different in different individuals, indicating cattle were not all born during a single birth season.

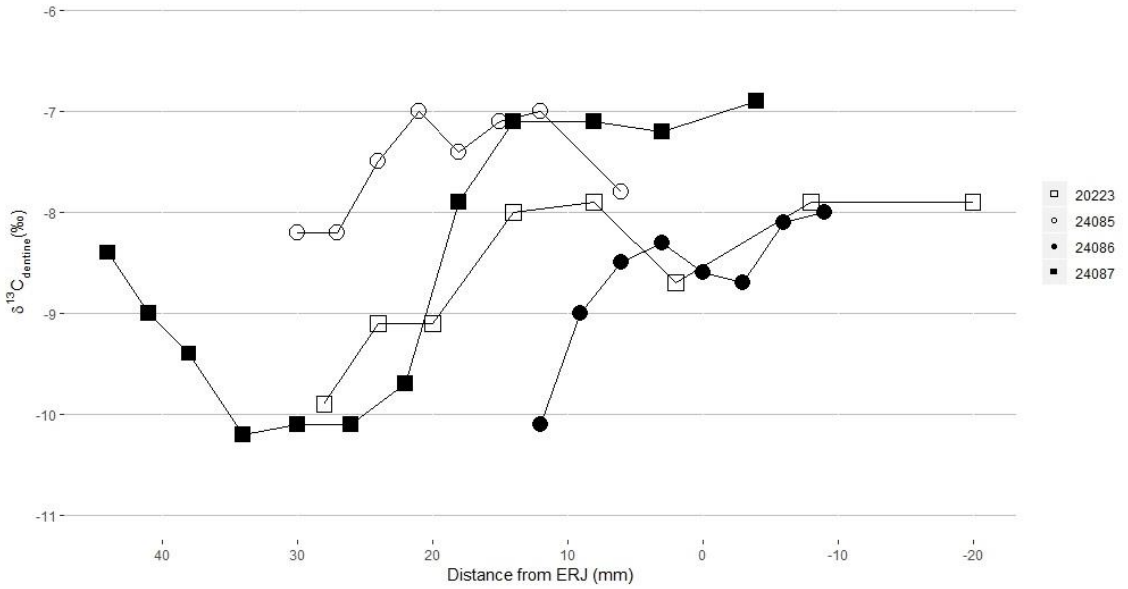


Figure 7.1: Trajectories of serial $\delta^{13}C_{enamel}$ values for five archaeological teeth

Cattle are less seasonal breeders than sheep and their fertility varies throughout the year (Dahl and Hjort, 1976). Provided that good grasses are plentiful (evidenced by the high $\delta^{13}C$ values in this dataset), it is possible for cattle to have more than one birth season, as reported in archaeological contexts in the Neolithic of Scandinavia (Kurt et al., 2015) and the Early Bronze Age of Britain (Towers et al., 2011). At Great Zimbabwe, variations in birth seasons in cattle must have involved a considerable human effort. The animals' diets during the dry winter months would have had to be sustained either through wild pasture, or by feeding on crop residues. The most likely motivators to encourage multiple births in a year are to provide a consistent milk or meat supply, and/or to increase the size of the herd. There is no ethnographic evidence for multiple birth seasons in cattle in Zimbabwe. All calves are born in spring.

From this dataset, it is not possible to comment on whether the cattle's diets were supplemented with crop residues. The principal Iron Age grain crops, millet and sorghum, are C_4 plants and therefore cannot be isotopically distinguished from wild C_4 grasses. Shifts in $\delta^{15}N$ values of animals consuming crop residues from intensively manured fields have been reported in previous studies (Fraser et al., 2011; Bogaard et al., 2013). This scale of manuring has not been documented in southern Zimbabwe and it is unlikely to

have occurred in the past. For these reasons, we cannot identify supplementary feeding on crop residues.

Could the intra-annual range of variation of diet observed in the cattle teeth be a consequence of seasonal variation in the $\delta^{13}C$ values of C_4 grasses? Despite reports to the contrary (e.g. Swap et al., 2004), $\delta^{13}C$ values of C_4 plants do respond to moisture availability (Buchmann et al., 1996; Murphy and Bowman, 2009), but this can make only a minor contribution to the large variation in $\delta^{13}C_{dentine}$, especially, seen in this study. This results from consumption of C_3 browse. The $\delta^{13}C$ values overall were high (for entire dataset, mean $\delta^{13}C_{enamel}$ = 1.31‰, mean $\delta^{13}C_{dentine}$ = -7.48‰) so only small amounts of C_3 browse were included in the diets. UCT24100 dates to AD250-400 and its diet was not measurably different from the other 26 individuals. In contemporary communities in the southern lowveld of Zimbabwe, cattle browse on C_3 plants during the dry winter months to obtain sufficient nutrients (Scoones, 1994; Smith, 2005; Smith et al., 2007). This is likely a consequence of both more restricted use of the landscape as a result of private farm ownership and a dry overgrazed environment. During the Great Zimbabwe period, cattle ate only small quantities of C_3 leaves and shrubs, so must have had access to C_4 grasses throughout the year. In a regional context, this pattern of a high consumption of C_4 grass has also been identified at Toutswe from AD700-1000 (Mosothwane, 2010), at various sites in the Shashe-Limpopo River Basin from AD900-1290 (Smith, 2005) and Khami from AD1475-1650 (Dyvart et al., 2018) and likely contributed to the success of these polities.

Stable isotope analysis of archaeological fauna from sites in the Shashe-Limpopo Basin revealed intermittent wet and dry periods in the Middle to Late Iron Age (Figure 7.2: lower $\delta^{15}N$ values during Leopard's Kopje A contemporaneous with K2, Leopard's Kopje B contemporaneous with Mapungubwe and Icon/Khami periods). Wet intervals have been reported from AD1430-1450 and AD1560-1575 (Huffman and Woodborne, 2016). Before and between these dates, the Shashe Limpopo River basin has been hypothesised to have experienced drought. Dyvart et al. (2018) reported low $\delta^{15}N$ values (<6.5‰) for *Bos taurus* excavated from the Late Iron Age site of Khami (Figure 7.2: dark blue triangles). The authors suggested that this may indicate higher rainfall than that in the Shashe-Limpopo Basin, but due to the multiple factors which influence $\delta^{15}N$ values of animal collagen, conclusions were tentative.

Environmental proxies from the last two millennia are frequently contradictory, but it is clear that the period AD1300-1600 experienced erratic environmental conditions. The $\delta^{13}C$ and $\delta^{15}N$ values for cattle from Great Zimbabwe are similar to those from Khami (Figure 7.2) and cattle in both polities had access to plentiful C_4 grasses throughout the year. This likely contributed to the rise of both societies to economic and political prominence in the region. Similarly, animals from Toutswe, and some from Leopard's Kopje A and Leopard's Kopje B periods fall within the same stable isotope ranges as those from Khami and Great Zimbabwe. These likely represent wetter years in these earlier periods, and therefore support a variable environment during the Middle Iron Age.

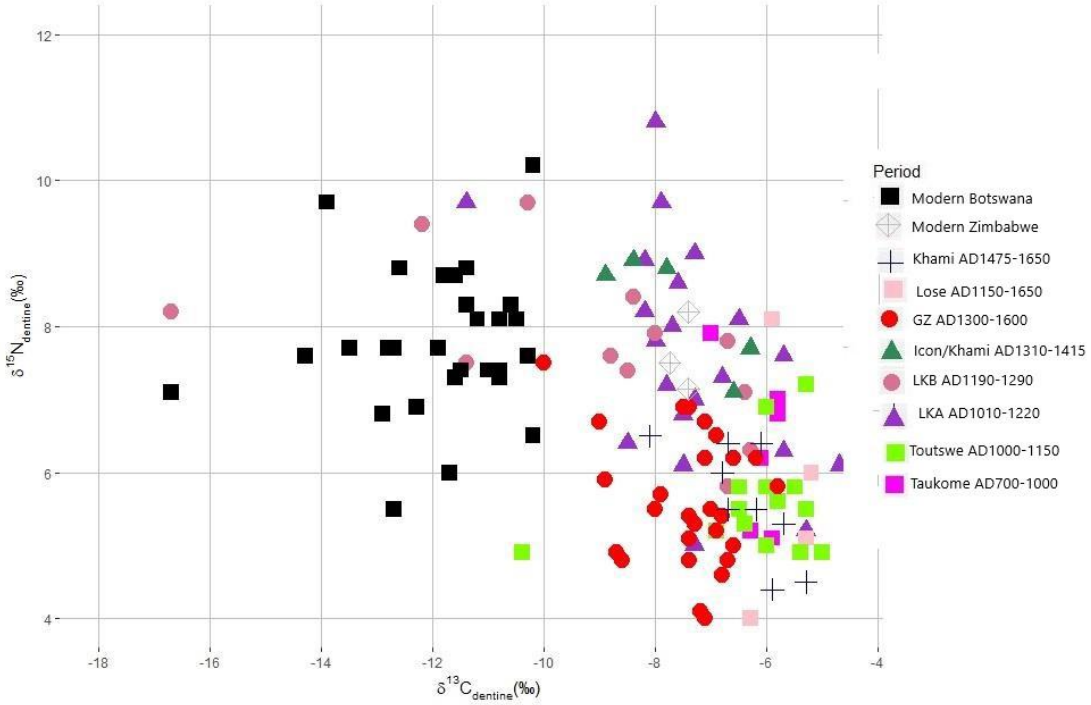


Figure 7.2: Scatter plot comparing $\delta^{13}C$ and $\delta^{15}N$ values of *Bos taurus* excavated from various Iron Age sites and periods in south-central Africa. Data compiled from Smith (2005), Mosothwane (2010) and Dyvart et al., (2018). Modern data has been corrected for the fossil fuel effect by adding 1.5‰ to the measured values. The values for GZ are the means of all the sub-samples per tooth, as presented in Chapter 6.

The stable isotope results from several studies show that cattle had access to C_4 grasses regardless of changing environmental conditions (Figure 7.2: most $\delta^{13}C_{dentine}$ values are >-8‰ from the Leopard's Kopje A to Khami periods indicating strongly grass-dominated diets). This is supported by the weak correlation ($R^2 = 0.3$) between the $\delta^{15}N$ and the $\delta^{13}C$ values i.e. if $\delta^{15}N$ values can be used as a proxy for moisture availability, then this dataset

shows that the quantity of C_4 grasses consumed does not depend on the level of moisture. In order for this to have occurred, an element of herd management to avoid overgrazing must have come into play. Importantly, this dataset confirms observations from other research (Mosothwane, 2010; Smith, 2005) which shows that today, $\delta^{15}N$ values tend to be more positive, and modern-day cattle consume much more browse than they did in the past. This is likely a consequence of environmental degradation as well as restricted availability of land for grazing.

The generally accepted hypothesis is that the cattle at Great Zimbabwe were not herded locally around the site because the population was so large that there was not enough space or resources to sustain large numbers of animals. Evidence in support of this theory includes the distribution of *madzimbahwe* along the edge of the Zimbabwe plateau (coinciding with the boundary of tsetse-fly) (Garlake, 1978). This distribution may relate to a settlement pattern in which herders used the winter sweetveld grasses off the plateau (i.e. in the lowveld) and summer sourveld grasses on the plateau (Garlake, 1978). This would have maximised year-round nutrient intake whilst avoiding the lethal tsetse-fly found in the lowveld in the summer rainy season (November to March). Today, transhumance is a common strategy implemented amongst rural herders in drought periods (Scoones, 1990). Further, Garlake (1978) suggested that if the cattle-herders had been able to rely entirely on the resources of the plateau, the distribution of Zimbabwe-type sites would be expected to encompass the whole plateau rather than be concentrated on the periphery.

In three individuals out of 27, patterns of variation in $^{87}Sr/^{86}Sr$ down the height of the crown are consistent with movement between geological substrates on the scale suggested by Garlake (1978). They are, of course, also consistent with the animals having lived near the boundary between two geological substrates, in which case they may have moved relatively little. Sinclair (1987) suggested that the site of Montevideo Ranch formed a satellite settlement within the Zimbabwe state and that the heterogenous nature of the vegetation in its immediate vicinity would make it a prime location for transhumance. The site is located on the border of two geological substrates (Figure 7.3), making it possible that the three teeth showing movement between geological substrates may come from animals raised at Montevideo Ranch or a similarly situated site. The fact that only three of 27 teeth show this pattern implies that if transhumance occurred on the scale suggested by Garlake (1978) and Sinclair (1987), it was a minor occurrence. Importantly,

since Garlake's (1978) study, many more Zimbabwe-type sites have been identified, scattered across the Zimbabwe plateau and beyond the edge of the plateau. In light of this more recent data, the correspondence between Zimbabwe-type sites and the boundary of the tsetse-fly distribution is much less neat. There are also likely to be as yet undiscovered unwalled Zimbabwe-type sites in these areas which fell within the catchment area of cattle supplied to Great Zimbabwe.

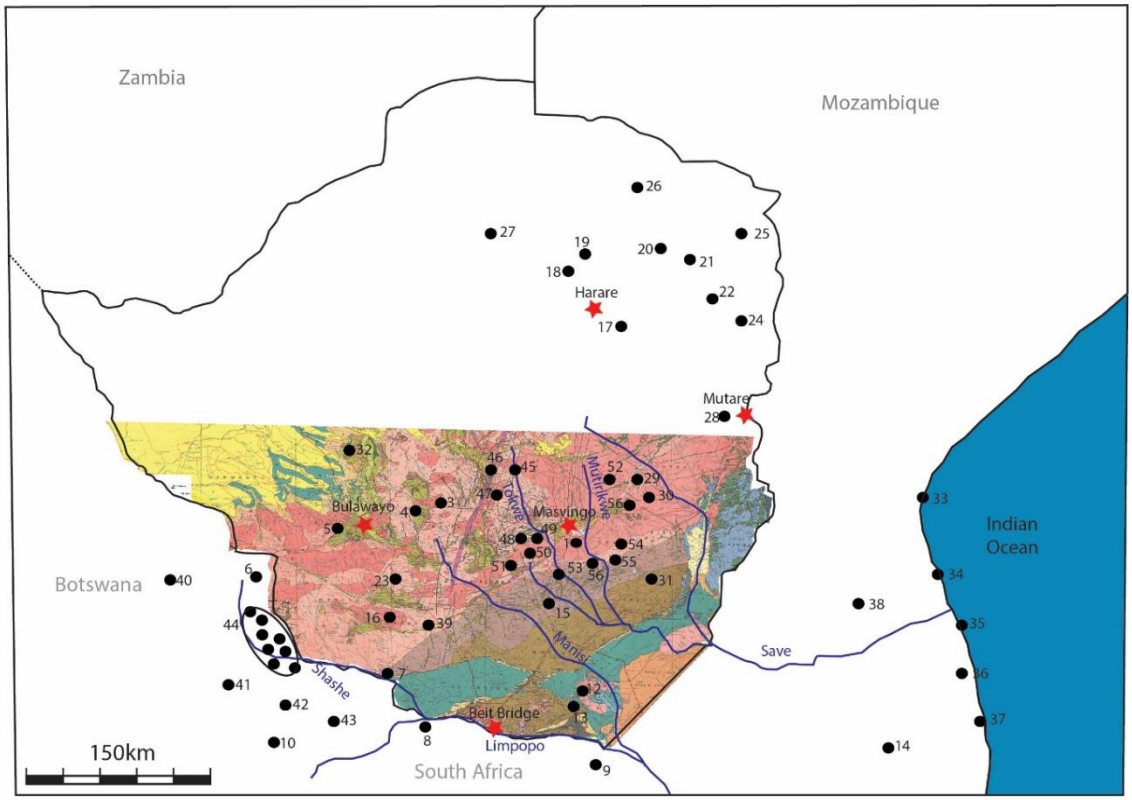
The majority of teeth in this study show $^{87}Sr/^{86}Sr$ profiles indicating that the animals were born on a geological substrate different from that at Great Zimbabwe and remained there for the first year of life. Based on the sample analysed in this study, most cattle supplied to Great Zimbabwe were sent from the lowveld region south of the Zimbabwe plateau. The implication is that either these herders had management strategies that enabled them to cope with tsetse-fly (as do some rural communities residing in this area today) or the tsetse-fly was not there during this period. Possible adaptations have been described in Chapter 3. One likely strategy would have been to clear the bushy vegetation around the homestead to eliminate shady places where the flies can pupate, so that the cattle can graze on the grass. Burning mopane trees and other shrubs on a wider scale would further deter the fly (Livingstone, 1857, Kirk, 1865; Torr, 2011). Garlake (1978) suggested that the boundaries of prosperous communities like Great Zimbabwe would expand their areas of bush clearance and drive the fly back entirely. These adaptation strategies are plausible, but tsetse-fly may simply have been less prevalent during this period. This is evidenced by the large number of archaeological cattle raised in modern-day tsetse-fly belts (Plug 1987; Manyanga, 2006). It may also be relevant to note the small amounts of C_3 browse consumed by cattle from the lowveld during this time. A similarly strong C_4 grazing signal was reported at Khami (Dyvart et al., 2018). Clearing bush as a means of tsetse fly control would have led to C_3 browse becoming less available.

Figure 7.3 is a map of Zimbabwe type sites overlain on a geological map of the south of the country. From their $^{87}Sr/^{86}Sr$ values, 21 of the teeth derive from cattle raised on gneisses, metasediments and paragneisses between 40 and 120kms south of Great Zimbabwe (shown in the grey and olive-green colours, Figure 7.3). Excavated sites in these zones include Montevideo Ranch, Chibvumani, Esquilingwe, Domboshoko and Chipukuswi. There are, however, many sites on these geological substrates which have yet to be investigated. Only three out of 27 teeth showed $^{87}Sr/^{86}Sr$ values consistent with animals raised on the young granite substrates over which Great Zimbabwe is situated

(shown in pink, Figure 7.3). Based on the age profiles of the cattle excavated from the Hill, both Garlake (1978) and Barker (1978) suggested that the breeding herds for Great Zimbabwe must have been kept further away from the site. Thorp (1995) later reported that there were some adult animals within the walled areas at the foot of the hill and the age profiles of the cattle indicated that indeed, some breeding herds may have been kept closer to the site. This research shows that both scenarios are likely to be true, but based on the teeth analysed here, the majority of the breeding herd was kept further away from Great Zimbabwe. The implication of this is that Great Zimbabwe had access to a much larger catchment area of cattle than previously thought. In this respect, this study has contributed significantly to our knowledge of breeding herds and herd management at Great Zimbabwe.

One conclusion that we can draw with confidence is that, in this sample set, none of the cattle were raised on the basalt geological substrate (shown in blue, Figure 7.3). There are two excavated sites here: Malumba and Mwenezi Hill. Manyanga (2006) classified both as Zimbabwe-type sites, primarily on the basis of their freestanding stone walling and ceramics but other research has suggested that they did not fall within the sphere of the Zimbabwe state (Gray, 2008). The latter view is based on declining evidence of occupation between AD1300 and AD1700, and differences in ceramic style between these sites and Great Zimbabwe. Whichever scenario is correct, it seems that the catchment area of cattle supplied to Great Zimbabwe does not extend this far south. However, faunal analysis has shown that wild animals (rather than domesticates) were the principal meat source at these sites (Manyanga, 2006; Gray, 2008). It may be that the environment in the area was not favourable for cattle raising, so any conclusion on this point is tentative.

It is important to remember that even though we now know that 21 of the cattle were born between 40 and 120kms away from the site, they were eventually taken to Great Zimbabwe (likely alive) to be consumed. The ages at death of the specimens have been estimated to be less than 18 months (Thorp, 1995). The crown of a *Bos taurus* M2 forms over approximately 12 months, starting from one month of age. This leaves a 6-month period (between the ages of 12 and 18 months) for which we lack information on where the animal was living. It was during this 6-month period that the animals would have been taken to Great Zimbabwe for slaughter.



Key

1)Great Zimbabwe	15)Chipukuswi	29)Chivowa	43)Bobonong
2)Zaka	16)Jahunda	30)Matendere	44)Mupani sites
3)Naletale	17)Tsindi	31)Chibvumani	45)Tokwe river
4)Danangombe	18)Chisvingo	32)Taba Zikamambo	46)Tamofu
5)Khami	19)Dambarare	33)Sofala 2	47)Chompungi
6)Domboshava	20)Ruanga	34)Muringare bay	48)Buhwa
7)Little Mapela	21)Mtoko	35)Sofala 1	49)Pamuuyu
8)Mapungubwe	22)Tere	36)Chibuene	50)Nenga Ruin
9)Thulamela	23)Chimnungwa	37)Vilanculos	51)Gorongwe 2
10)Lose	24)Njamara	38)Hofane	52)Runyani
12)Mwenezi	25)Luanze	39)Macardon	53)Domboshoko
13)Malumba	26)Baranda	40)Toranju	54)Masedzera
14)Manyikeni	27)Angwa	41)Bosutswe	55)Esquilingwe
	28)Manyika	42)Toutswe	56)Montevideo Ranch

Figure 7.3: Geological map of southern Zimbabwe showing archaeological sites occupied during the Zimbabwe Period (drawn by M. House)

In West Africa, investing more time and resources into a specialised economy has been associated with politically complex systems (McIntosh, 1999). Using McIntosh's (1999) model, one would expect that, as Great Zimbabwe expanded, the area over which it had political control, from AD1300 onwards, there would be shifts in herd management strategies as the population increased and as resources had to be managed. However, the 20 teeth from the AD1300-1400 occupation fell within the same stable isotopic ranges as the six dated to AD1400-1600. In other words, there is no detectable shift in herd

management practices through time. This issue should be examined further using larger sample sizes.

The implication of smaller Zimbabwe-type sites being responsible for herding cattle and sending them to Great Zimbabwe raises some important points about the way in which archaeologists attribute value to the distribution of economic resources within politically complex systems. Mafeje (1991) suggested that, whilst there is political ranking in African polities, all spheres have access to the same economic resources. Thorp (1995), on the other hand, suggested that it was unlikely that the elite and commoners at Great Zimbabwe had access to the same herds. Other researchers (e.g. Huffman, 1996; 2010) have associated particular types of material culture (for example gold, exotic imports and stone walling) with elite and commoner groups. This study shows that cattle excavated in unwalled 'commoner' areas of Great Zimbabwe derived from the same catchment areas and had similar dietary signature ranges to those from the 'elite' walled areas of the site. Elite and commoner groups at Great Zimbabwe may well have had access to the same herds. This supports the conclusion drawn by Chiripanhura (2017) that the same animal may have been distributed across the site in a meat-sharing practice resulting in the same isotopic signatures being reflected in elite and commoner areas. There were, however, only 7 teeth excavated from unwalled areas, and 20 from the walled areas so limitations of sample size mean that this suggestion is tentative.

Hall (1986) broadly separated the significance of cattle into 'allocative' resources which include hides, milk and meat, and 'authoritative' resources which include the social significance of cattle (e.g. marriage transactions and ceremonial sacrifices). In the archaeological record, it is difficult to distinguish these roles. Cattle were certainly consumed as meat and milk. Hall (1986) suggested that once complex state systems had developed on the Zimbabwe plateau and surrounds, the rulers depended more on exotic imports as status indicators than cattle. In contrast, Reid (1996) suggested that, despite exotic imports having a considerable effect on their economies, the basic social and political structures of these polities were little affected. The results of this study show that cattle were being sourced from as far as 120kms away from Great Zimbabwe. This certainly emphasises the importance of the resource in both allocative and authoritative capacities.

The most recent research into the economy of the Zimbabwe state argues that it was a dispersed production system rather than a centralised one (Chirikure, 2015; Chirikure,

2019). This is evidenced by the small strews of production debris (e.g. metal-working, salt and ivory) recovered from Great Zimbabwe itself and surrounding contemporary sites. Households were responsible for their own craft production, which indicates that no specialised craft production or division of labour existed (Bandama et al., 2017; Chiripanhura, 2017; Chirikure, 2019). Imported goods were more widely distributed than previously realised, both at the site and beyond, and gold, iron, copper and tin from a variety of sources were exchanged. There may have been centralised grain storage facilities, but most grain was probably kept and controlled by individual households. Complex internal exchange networks circulated resources throughout the state in a decentralised manner where stone walls, ancestors and cattle provided symbolic power and wealth to its leaders (Chirikure, 2019). Importantly, the lack of centralisation in the Zimbabwe state is in contrast to state systems such as those in Mesopotamia and ancient Egypt where elites centralised and monopolised the economy (Stein, 1998).

In light of this, the findings of this study have important broader implications for how the Zimbabwe state functioned, with a variety of key local economic resources being exchanged through time. Great Zimbabwe's economy depended on extensive cultivation and pastoralism to support the c. 10 000 occupants of the site. Throughout the period of prosperity of the Zimbabwe state, cattle formed a vital branch of production. This is further evidenced in smaller Zimbabwe-type sites which yielded large numbers of cattle, including Chivowa Hill, Tsindi (Rudd, 1968), Montevideo Ranch (Sinclair, 1987), Ruanga and Nhunguza (Garlake, 1973). This study supports the argument of Sinclair (1987) that the very large numbers of cattle eventually sent to Great Zimbabwe were built up in the good grazing areas in the south of modern-day Zimbabwe. Cattle breeding was not subject to the same limitations as crop agriculture. Cattle herders made good use of savanna and bush-veld environments, and large herds would have provided some insurance against the annual risk of drought and crop failure, and therefore a secure means of preserving surplus wealth. Evidence from this study emphasizes that smaller sites within the Zimbabwe state - up to 120 km from Great Zimbabwe - played an integral role in the cattle economy. The inference is that, like other local commodities, cattle too were managed as part of a de-centralised political economy. The fact that cattle were sourced from across such a wide landscape emphasises the extent of local trade and exchange networks in the Zimbabwe state.

These implications clearly relate to the relative importance of local and international trade within the Zimbabwe state. While Great Zimbabwe was intensely involved in the trade of exotic goods such as glass beads, cloth and porcelain (Huffman, 2007; Collett 1992), there is a need to assess more closely the role of local trade in the form of iron gongs, cattle and ceramics (Pikirayi, 2001; Chirikure, 2019). Opportunities for these kinds of studies are abundant with the existence of thousands of cattle bones, iron objects and production debris and thousands of ceramics excavated from the site.

The *Bos taurus* second molar dated in this study to 1710±30 (AD250-436) is the earliest directly dated evidence for cattle in southern Africa and therefore can contribute to debates around the arrival of cattle in the region.

7.4 Limitations and future work

A number of limitations were encountered in this study. Multiple isotope pairs were measured in 27 individual cattle teeth, and although this is perhaps the largest sample size of one species in this kind of isotopic study, the author is aware that this is a small number of specimens compared with the thousands of cattle present at the site (Brain, 1974; Thorp, 1995). As such, the data presented here does not reflect animal husbandry practices for all cattle at the site, but only for the specimens analysed. Far more specimens will need to be analysed in the future to obtain an accurate picture of animal husbandry practices through time and space.

The stratigraphic contexts of the teeth from the Hodges Midden are poorly documented. Individual teeth cannot be associated with specific stratigraphic layers or levels, although material in different bags was labelled as deriving from different stratigraphic layers. As such, six teeth (at least one from each unlabelled layer) were radiocarbon dated to provide context. The radiocarbon dates fall within the time period of occupation on the hilltop.

Given the heterogeneity of the geology in the study region combined with the targeted research questions, it was adequate for this study to treat each major geological substrate as one unit. The ranges of $^{87}Sr/^{86}Sr$ values measured in vegetation from the various units separated sufficiently to distinguish the plateau from the Lowveld (and the basalts further to the south). This was adequate to answer the questions posed. More highly resolved $^{87}Sr/^{86}Sr$ sampling in the future may be able to add to the conclusions drawn in this thesis.

Enamel and dentine are deposited in incremental layers, so that sub-sampling the teeth using the method outlined above introduces a time-averaging effect, reducing the resolution of the time series. However, this study focussed on changes in isotopic ratios over periods of one year, rather than shorter-term changes. It might be beneficial to conduct more highly resolved serial sampling of the teeth in the future to capture smaller changes in diet.

Future work should also target smaller Zimbabwe-type sites in the lowveld region of Zimbabwe to explore in more detail local trade between them and Great Zimbabwe.

7.5 Conclusion

This study undertook carbon, nitrogen, oxygen and strontium isotope analyses of serial samples of 27 archaeological cattle teeth excavated from Great Zimbabwe to investigate cattle procurement and herd management strategies from AD1300 to AD1600. The relatively large sample size and the use of multiple isotopes provide an important addition to previous research into similar questions. These results significantly refine our understanding of the environment in the Iron Age, the importance of cattle as a key component and the flow of local economic resources within the Zimbabwe state. Returning to the research questions posed in Chapter 1, it is now possible to infer the following:

- How much diversity was there in pasturing strategies in cattle supplied to Great Zimbabwe?

Most cattle in this study ate predominantly C_4 grasses over the period of tooth growth. A few individuals consumed a little C_3 browse and one consistently fed on C_3 browse. This heterogeneity in diet is not related to excavation area or time period, and likely reflects animals originating from multiple herds.

- Was there more than one birth season in cattle supplied to Great Zimbabwe?

Different trajectories of $\delta^{13}C$ values up the heights of the teeths show that calves were probably born in more than one season. Cattle were being managed in such a way as to build up the herds for economic and/or political reasons.

- Was there seasonal movement of cattle herds (transhumance) across the landscape from the immediate vicinity of Great Zimbabwe to areas further away as proposed by previous researchers?

Serial $^{87}Sr/^{86}Sr$ samples show that transhumance was not the norm. Three out of 27 animals may have been transhumant, or may simply have lived near a geological boundary.

- How widely across the landscape were cattle sourced for slaughter at Great Zimbabwe?

$\delta^{18}O$ and $^{87}Sr/^{86}Sr$ combined show that the catchment area from which the people of Great Zimbabwe obtained their cattle was very large. Most animals were born and grew up in the lowveld region between 40 and 120kms south of the site. Today this region is dry but offers good grazing. It is, however, a tsetse fly area. If tsetse fly was present at the time of Great Zimbabwe, strategies may have been employed to mitigate its impact. Future work should integrate this information into our wider understanding of the extent of Great Zimbabwe's influence across the region.

This study implies that lesser studied 'rural' communities within the Zimbabwe state were important participants in local trade networks. Cattle are likely to have been used in establishing and negotiating power relations between centres. These dynamics were almost certainly at play between rural sites and the core of the state at Great Zimbabwe.

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APPENDICES

Appendix 1: Mean values and standard deviations of repeated measurements of standards for inorganic (enamel apatite) analyses, per run. Figures are 'raw' values, subsequently corrected to values in italics in second row of each block.

Run	**Values**	**CM***	**NBS 19**	**NBS 18**	**Values**	**CM***	**NBS 19**	**NBS 18**
		0.34	***1.95***	***-5.05***		***-8.95***	***-2.20***	***-23.03***
1	$\delta^{13}C$	0.59	0.89	-6.03	$\delta^{18}O$	-11.74	-7.98	-25.84
	StdDev	0.07	0.13	0.06	StdDev	0.06	0.06	0.06
2	$\delta^{13}C$	0.73	2.28	-4.67	$\delta^{18}O$	-11.23	-4.83	-25.57
	StdDev	0.04	0.10	0.16	StdDev	0.09	0.12	0.09
3	$\delta^{13}C$	0.68	2.26	-4.59	$\delta^{18}O$	-11.27	-4.80	-25.45
	StdDev	0.07	0.05	0.03	StdDev	0.04	0.10	0.09
4	$\delta^{13}C$	-0.88	0.72	-6.20	$\delta^{18}O$	-11.76	-5.12	-26.04
	StdDev	0.08	0.05	0.12	StdDev	0.09	0.02	0.12
5	$\delta^{13}C$	-0.84	0.77	-6.27	$\delta^{18}O$	-11.69	-5.08	-25.96
	StdDev	0.06	0.06	0.08	StdDev	0.07	0.03	0.10
6	$\delta^{13}C$	0.73	2.28	-4.70	$\delta^{18}O$	-11.23	-4.83	-25.57
	StdDev	0.04	0.10	0.07	StdDev	0.09	0.12	0.09
7	$\delta^{13}C$	-0.74	0.91	-6.02	$\delta^{18}O$	-11.63	-4.98	-25.65
	StdDev	0.08	0.01	0.02	StdDev	0.09	0.05	0.06
8	$\delta^{13}C$	-0.65	1.00	-6.00	$\delta^{18}O$	-12.01	-5.03	-25.86
	StdDev	0.11	0.04	0.02	StdDev	0.07	0.09	0.10
Run	**Values**	**Carrara Z**	**CM***	**Lincoln Limestone**	**Values**	**CM***	**Lincoln Limestone**	**Carrara Z**
		2.25	***0.34***	***1.10***		***-8.95***	***-10.44***	***-1.27***

9	$\delta^{13}C$	1.16	-0.58	0.06	$\delta^{18}O$	-4.88	-11.46	-13.11
	StdDev	0.06	0.10	0.11	StdDev	0.09	0.14	0.11
10	$\delta^{13}C$	1.17	2.27	0.42	$\delta^{18}O$	-10.44	-1.55	-8.86
	StdDev	0.07	0.07	0.03	StdDev	0.11	0.13	0.07
11	$\delta^{13}C$	2.20	1.03	0.42	$\delta^{18}O$	-1.36	-10.44	-8.83
	StdDev	0.16	0.10	0.12	StdDev	0.16	0.14	0.16
12	$\delta^{13}C$	0.89	2.09	0.22	$\delta^{18}O$	-10.13	-1.14	-8.64
	StdDev	0.18	0.11	0.11	StdDev	0.18	0.08	0.15

Appendix 2: Mean values and standard deviations of repeated measurements of standards for organic (dentine collagen) analyses per run. Figures are 'raw' values, subsequently corrected to values in italics in second row of each block.

Run	**Values**	**Choc** ***4.31***	**Seal** ***15.84***	**Valine** ***12.14***	**Values**	**Choc** ***-17.75***	**Seal** ***-11.97***	**Valine** ***-26.80***
1	$\delta^{15}N$	3.93	15.36	11.73	δ13C	-18.45	-12.81	-11.01
	StdDev	0.04	0.03	0.05	StdDev	0.17	0.10	0.08
	Values	**Choc** ***4.31***	**Sucrose**	**Valine** ***12.14***	**Values**	**Choc** ***-17.75***	**Sucrose** ***-10.60***	**Valine** ***-26.8***
2	$\delta^{15}N$	3.89		11.69	$\delta^{13}C$	-18.44	-11.08	-27.52
	StdDev	0.07		0.11	StdDev	0.08	0.08	0.07
3	$\delta^{15}N$	4.45		12.34	$\delta^{13}C$	-18.54	-11.10	-27.55
	StdDev	0.13		0.09	StdDev	0.04	0.04	0.05
4	$\delta^{15}N$	4.26		12.07	$\delta^{13}C$	-18.49	-11.11	-27.57
	StdDev	0.03		0.04	StdDev	0.07	0.09	0.07
5	$\delta^{15}N$	4.38		12.24	$\delta^{13}C$	-18.81	-11.34	-27.72
	StdDev	0.04		0.07	StdDev	0.09	0.08	0.10
6	$\delta^{15}N$	4.50		12.33	$\delta^{13}C$	-19.03	-11.70	-27.97
	StdDev	0.09		0.08	StdDev	0.14	0.14	0.16
7	$\delta^{15}N$	4.47		12.25	$\delta^{13}C$	-19.12	-11.71	-28.11
	StdDev	0.08		0.04	StdDev	0.06	0.09	0.02
8	$\delta^{15}N$	4.32		12.20	$\delta^{13}C$	-18.72	-11.28	-27.85
	StdDev	0.02		0.02	StdDev	0.06	0.03	0.07
9	$\delta^{15}N$	4.07		11.84	$\delta^{13}C$	-18.54	-11.07	-27.54
	StdDev	0.06		0.04	StdDev	0.11	0.11	0.11
10	$\delta^{15}N$	4.22		12.11	$\delta^{13}C$	-18.94	-11.59	-27.96
	StdDev	0.06		0.14	StdDev	0.06	0.12	0.08

11	$\delta^{15}N$	4.18		12.04	$\delta^{13}C$	-18.84	-11.42	-27.82
	StdDev	0.06		0.12	StdDev	0.07	0.06	0.06

Appendix 3: All isotope data for archaeological serial samples. Note: dentine collagen samples in grey did not meet preservation requirements and were not included in this study

Tooth number	mm from ERJ	$^{87}Sr/^{86}Sr$	mm from ERJ	$\delta^{13}C_{enamel}$ (‰)	$\delta^{18}O$ (‰)	mm from ERJ	$\delta^{13}C_{dentine}$ (‰)	$\delta^{15}N$ (‰)	Weight %N	Weight %C	C:N ratio (atomic)
20217	52	0.7338	50	1.3	-0.8	4	-12.4	7.6	11.1	20.2	3.4
20217	NA	NA	47	1.6	-0.2	10	-10.0	7.0	10.5	19.1	3.2
20217	48	0.7373	44	1.6	-0.3	16	-8.8	6.8	8.5	25.1	2.9
20217	46	0.7368	41	1.4	-0.6	22	-7.9	6.3	10.2	24.9	2.8
20217	44	0.7285	38	1.5	-0.5	26	-7.8	6.6	11.1	25.2	3.2
20217	42	0.7359	35	1.6	-0.7	30	-6.8	6.8	13.5	38.5	3.3
20217	40	0.7410	32	1.5	-0.7	34	-7.2	6.8	13.3	38.8	3.4
20217	38	0.7368	28	1.7	-1.5	38	-6.8	6.7	14.5	40.4	3.3
20217	36	0.7345	26	1.7	-1.5	42	-7.1	7.1	14.9	42.0	3.3
20217	34	0.7336	23	1.8	-1.6	46	-6.7	6.2	14.8	42.1	3.3
20217	32	0.7342	18	2.0	-1.7	50	-7.3	6.7	14.5	43.0	3.4
20217	30	0.7398	15	1.7	-1.6						
20217	28	0.7337	12	2.0	-2.0						
20217	26	0.7343	9	1.7	-1.7						
20217	24	0.7351	7	2.1	-1.9						
20217	22	0.7336	5	2.2	-1.7						
20217	20	0.7344	3	2.0	-1.5						
20217	18	0.7369	2	1.7	-1.5						
20217	16	0.7347	0	1.8	-1.9						
20217	14	0.7369									
20217	12	0.7323									

20217	10	0.7343									
20217	8	0.7380									
20217	6	0.7339									
20217	4	0.7343									
20217	2	0.7379									
20217	0	0.7392									
20218	38	0.7304	34	1.4	-1.7	-12	-7.5	6.5	12.6	36.0	3.3
20218	36	0.7333	32	1.2	-1.8	-9	-6.8	6.3	13.3	37.2	3.3
20218	34	0.7349	30	1.3	-1.7	-6	-7.2	6.2	13.2	29.5	3.3
20218	32	0.7331	28	1.4	-1.4	-3	-7.0	6.4	14.0	39.1	3.3
20218	30	0.7329	26	1.5	-1.0	0	-6.4	6.4	13.3	38.2	3.3
20218	28	0.7322	24	1.8	-1.4	4	-6.8	6.4	13.9	38.6	3.2
20218	26	0.7301	22	1.8	-1.9	7	-6.8	6.5	13.9	39.2	3.3
20218	24	0.7291	20	1.6	-2.5	10	-6.7	6.4	14.3	40.6	3.3
20218	22	0.7300	18	1.3	-2.8	14	-6.7	6.5	15.3	43.5	3.3
20218	20	0.7314	15	1.1	-2.3	18	-6.8	6.7	12.9	37.1	3.4
20218	18	0.7306	13	1.3	-1.6	22	-6.9	6.8	13.8	38.9	3.3
20218	16	0.7335	10	1.2	-1.6	26	-6.8	6.8	16.0	44.3	3.2
20218	14	0.7305	8	1.3	-2.3						
20218	12	0.7361	6	1.1	-1.9						
20218	10	0.7287									
20218	8	0.7305									
20218	6	0.7299									
20218	4	0.7300									
20218	2	0.7336									
20218	0	0.7309									
20220	28	0.7692	26	2.7	-1.6	-20	-8.1	6.1	13.3	38.2	3.3
20220	26	0.7683	24	2.8	-2.4	-16	-8.5	6.9	11.6	25.1	2.9
20220	24	0.7686	22	2.8	-2.8	-12	-8.1	6.4	9.2	38.1	2.9
20220	22	0.7686	20	2.9	-3.2	-8	-7.5	7.1	14.9	41.1	3.2
20220	20	0.7676	17	2.9	-3.6	-4	-8.2	6.9	14.6	40.7	3.3

20220	18	0.7674	14	2.6	-3.6	-2	-8.5	6.7	9.1	20.1	3.2
20220	16	0.7683	10	2.7	-3.5	8	-6.9	6.2	13.5	30.1	3.4
20220	14	0.7676	8	2.7	-3.3	14	-9.0	5.9	8.9	29.6	3.1
20220	12	0.7669	6	2.4	-3.1	18	-7.2	5.6	9.6	28.2	2.9
20220	10	0.7666	4	2.8	-2.4	22	-6.0	6.0	13.0	37.0	3.3
20220	8	0.7695	2	2.8	-2.8	26	-6.0	6.0	13.2	37.4	3.3
20220	6	0.7662	0	2.6	-4.2						
20220	4	0.7691									
20220	2	0.7702									
20220	0	0.7650									
20223	28	0.7891	28	1.1	-1.2	-20	-7.9	5.1	14.1	32.1	3.5
20223	26	0.7889	24	1.4	-2.9	-16	-8.4	5.1	10.7	32.0	3.4
20223	24	0.7883	22	2.0	-2.7	-12	-8.6	5.5	8.2	24.9	3.5
20223	22	0.7885	20	1.9	-3.9	-8	-7.9	5.4	12.5	28.3	3.3
20223	20	0.7881	18	2.4	-4.1	-4	-8.5	5.5	9.5	27.2	3.3
20223	18	0.7861	16	2.3	-3.6	2	-8.7	5.7	11.1	28.2	3.4
20223	16	0.7853	14	2.5	-2.9	8	-7.9	5.5	11.6	28.5	3.1
20223	14	0.7879	12	2.1	-3.5	14	-8.0	5.6	11.3	29.4	3.0
20223	12	0.7883	10	1.9	-3.8	20	-9.1	5.6	11.8	29.8	3.3
20223	10	0.7887	8	1.9	-3.9	24	-9.1	5.5	12.5	28.3	3.4
20223	8	0.7879	6	1.4	-3.3	28	-9.9	5.5	12.2	28.1	3.4
20223	6	0.7881	4	1.2	-3.7						
20223	4	0.7871	2	1.0	-3.5						
20223	2	0.7890	0	1.1	-2.5						
20223	0	0.7892									
20226	46	0.7482	43	2.7	-0.7	-2	-7.0	5.3	13.0	39.3	3.5
20226	44	0.7452	40	2.8	0.2	3	-6.7	4.7	12.6	37.6	3.5
20226	42	0.7455	37	2.6	0.1	14	-7.2	4.8	12.9	37.8	3.4
20226	40	0.7498	34	2.6	0.2	22	-6.2	4.7	12.1	36.4	3.5
20226	38	0.7505	31	2.7	0.3	30	-6.4	4.6	12.5	37.0	3.5
20226	36	0.7510	28	2.5	0.6	38	-6.8	4.3	7.2	21.3	3.4

20226	34	0.7442	25	2.4	0.2	46	-6.8	4.6	11.7	35.4	3.5
20226	32	0.7467	19	2.3	0.6						
20226	30	0.747	16	2.0	1.1						
20226	28	0.7493	13	2.3	1.1						
20226	26	0.7480	10	2.2	1.3						
20226	24	0.7467	7	2.1	1.6						
20226	22	0.7471	5	2.2	1.5						
20226	20	0.7431	4	2.2	2.0						
20226	18	0.7411	3	2.4	1.2						
20226	16	0.7406	2	2.7	0.8						
20226	14	0.7396	0	2.9	0.7						
20226	12	0.7405									
20226	10	0.7424									
20226	8	0.7418									
20226	6	0.7442									
20226	4	0.7403									
20226	2	0.7503									
20226	0	0.7487									
20228	38	0.7363	37	3.3	-2.0	-12	-6.4	5.8	15.8	44.2	3.3
20228	36	0.7431	34	3.1	-0.1	-9	-6.3	5.9	16.2	44.9	3.2
20228	34	0.7360	31	3.2	1.0	-6	-6.0	5.9	16.2	45.3	3.3
20228	32	0.7420	28	3.1	1.1	-3	-6.0	5.8	15.8	43.9	3.2
20228	30	0.7325	25	2.8	1.4	0	-6.0	6.2	15.4	42.8	3.2
20228	28	0.7347	22	2.8	1.3	4	-6.1	5.8	15.2	44.1	3.2
20228	26	0.7335	17	3.0	0.6	7	-6.0	5.5	15.8	44.0	3.2
20228	24	0.7333	13	3.0	-0.4	10	-6.2	6.2	15.8	43.9	3.2
20228	22	0.7319	8	2.9	-0.8	14	-6.5	6.0	15.8	43.9	3.2
20228	20	0.7325	6	3.0	-0.7	18	-6.4	6.5	15.5	42.9	3.2
20228	18	0.7325	4	2.9	-0.3	22	-6.1	6.6	16.1	44.5	3.2
20228	16	0.7398	3	3.1	-0.7	26	-6.0	6.7	15.8	44.2	3.2
20228	14	0.7367	1	3.3	-1.0	30	-6.1	6.7	16.3	44.4	3.2

20228	12	0.7321				34	-6.2	7.0	15.6	44.1	3.3
20228	10	0.7314				37	-6.0	7.0	15.7	44.2	3.3
20228	8	0.7377									
20228	6	0.7352									
20228	4	0.7351									
20228	2	0.7446									
20228	0	0.7381									
20231	54	0.7546	54	1.7	-1.9	10	-7.8	4.2	11.5	29.2	3.4
20231	52	0.7534	51	1.6	-1.9	14	-6.9	2.8	12.1	32.7	3.2
20231	50	0.7562	48	1.7	-2.3	18	-8.8	4.6	6.7	20.3	3.5
20231	48	0.7509	45	1.9	-2.4	22	-6.5	3.0	11.1	29.8	3.3
20231	46	0.7508	41	1.9	-1.6	26	-8.0	3.5	7.1	20.8	3.4
20231	44	0.7455	38	2.6	-1.4	30	-7.7	3.5	14.6	41.3	3.3
20231	42	0.7468	35	2.1	-1.6	34	-7.4	3.9	12.3	35.2	3.3
20231	40	0.7463	32	2.0	-1.7	38	-7.1	4.7	14.9	41.1	3.2
20231	38	0.7507	27	1.9	-1.5	42	-7.3	3.4	14.9	42.2	3.3
20231	36	0.7489	24	1.9	-1.8	46	-7.2	3.4	14.6	41.5	3.3
20231	34	0.7508	22	1.9	-2.0	50	-6.9	3.4	14.4	41.2	3.3
20231	32	0.7468	18	1.5	-1.9	52	-5.9	4.5	14.7	41.1	3.3
20231	30	0.7479	16	1.2	-1.9						
20231	28	0.7505	14	1.0	-1.6						
20231	26	0.7415	10	0.8	-1.2						
20231	24	0.7477	7	0.5	-0.9						
20231	22	0.7505	5	0.4	-0.7						
20231	20	0.7489	2	0.3	-0.4						
20231	18	0.7537									
20231	16	0.7521									
20231	14	0.7505									
20231	12	0.7515									
20231	10	0.7512									
20231	8	0.7502									

20231	6	0.7495									
20231	4	0.7494									
20231	2	0.7512									
20231	0	0.7498									
24083	38	0.7305	44	2.1	0.9	-6	-6.6	4.9	12.3	29.1	3.3
24083	36	0.7262	41	2.1	-0.8	-3	-6.4	5.0	13.2	36.8	3.3
24083	34	0.7251	37	2.2	0.6	4	-6.9	5.2	12.8	36.2	3.3
24083	32	0.7244	33	2.2	-0.3	8	-6.0	4.9	11.8	33.9	3.3
24083	30	0.7235	29	2.1	-0.2	12	-6.5	5.2	11.1	30.2	3.3
24083	28	0.7237	25	2.1	-1.4	16	-6.7	5.2	12.8	35.7	3.3
24083	26	0.7231	21	2.0	-1.6	20	-6.5	4.8	12.7	36.7	3.4
24083	24	0.7234	16	2.0	-0.5	24	-6.2	5.4	12.7	36.9	3.4
24083	22	0.7224	11	1.9	-0.6	28	-7.9	5.7	12.6	36.6	3.4
24083	20	0.7237	7	1.9	-0.9						
24083	18	0.7239	3	2.1	-0.7						
24083	16	0.7234	1	2.4	-0.6						
24083	14	0.7248									
24083	12	0.7248									
24083	10	0.7279									
24083	8	0.7248									
24083	6	0.7225									
24083	4	0.7253									
24083	2	0.7249									
24083	0	0.7224									
24084	38	0.7412	44	0.3	0.2	-15	-8.6	3.4	11.2	32.9	3.3
24084	36	0.7413	41	0.7	0.3	-12	-8.0	3.4	11.1	31.6	3.2
24084	34	0.7401	37	1.2	0.3	-9	-8.1	3.8	11.2	33.2	3.3
24084	32	0.7479	33	1.8	0.2	-6	-8.0	3.9	12.1	32.6	3.3
24084	30	0.7463	29	2.1	-0.1	-3	-8.0	4.1	11.6	35.4	3.5
24084	28	0.7403	25	2.4	0.1	3	-7.6	3.7	12.6	36.7	3.4
24084	26	0.7385	21	2.5	-0.1	6	-7.3	3.7	12.3	36.1	3.4

24084	24	0.7371	16	2.6	-0.2	9	-7.0	3.8	12.7	36.7	3.4
24084	22	0.7371	11	2.5	-0.2	12	-7.1	3.8	12.7	36.9	3.4
24084	20	0.7372	9	2.1	-0.2	15	-7.0	3.9	12.6	36.6	3.4
24084	18	0.7367	7	1.8	-0.2	18	-6.9	4.0	12.7	37.2	3.4
24084	16	0.7361	5	1.5	-0.2	21	-7.1	3.9	12.5	36.3	3.4
24084	14	0.7381	3	1.3	-0.3	24	-6.8	4.2	13.9	39.2	3.3
24084	12	0.7392	1	1.4	-0.1	27	-6.9	4.3	14.9	41.8	3.3
24084	10	0.7382				30	-7.2	4.7	14.5	40.8	3.3
24084	8	0.7374				33	-7.4	5.2	14.6	40.7	3.3
24084	6	0.7367				36	-6.8	4.2	13.6	38.9	3.3
24084	4	0.7376				39	-6.2	4.0	14.4	40.4	3.3
24084	2	0.7378				42	-6.3	3.9	14.2	40.1	3.3
24085	46	0.7297	43	0.5	0.2	6	-7.8	5.5	13.1	37.8	3.4
24085	44	0.7301	39	0.1	0.1	9	-8.6	5.6	4.3	20.2	3.5
24085	42	0.7302	35	0.0	0.0	12	-7.0	6.0	11.4	31.9	3.3
24085	40	0.7311	32	0.2	0.2	15	-7.1	6.2	12.9	36.1	3.3
24085	38	0.7318	29	0.6	0.1	18	-7.4	6.5	12.9	36.1	3.3
24085	36	0.7318	26	1.0	-0.1	21	-7.0	6.6	13.2	37.2	3.3
24085	34	0.7317	23	1.3	-0.1	24	-7.5	7.4	13.1	36.8	3.3
24085	32	0.7323	19	1.1	-0.2	27	-8.2	9.0	12.8	35.9	3.3
24085	30	0.7326	16	2.1	-0.4	30	-8.2	10.3	12.9	35.9	3.2
24085	28	0.7328	13	2.0	-0.2						
24085	26	0.7334	10	2.0	-0.2						
24085	24	0.7352	7	1.5	-0.2						
24085	22	0.7349	3	1.2	-0.3						
24085	20	0.7335									
24085	18	0.7340									
24085	16	0.7329									
24085	14	0.7350									
24085	12	0.7340									
24085	10	0.7345									

24085	8	0.7343									
24085	6	0.7345									
24085	4	0.7339									
24085	2	0.7334									
24085	0	0.7334									
24086	52	0.7755	44	1.5	-0.1	-9	-8.0	4.6	14.6	39.8	3.2
24086	50	0.7817	41	1.7	-0.5	-6	-8.1	4.5	14.8	39.9	3.2
24086	48	0.7820	37	1.5	-0.1	-3	-8.7	4.8	14.5	39.1	3.2
24086	46	0.7832	33	1.5	-0.5	0	-8.6	4.8	14.4	37.7	3.1
24086	44	0.7833	29	1.1	-0.4	3	-8.3	4.8	13.9	38.8	3.3
24086	42	0.7831	25	0.8	-0.2	6	-8.5	4.5	14.5	40.5	3.3
24086	40	0.7832	21	0.5	-0.4	9	-9.0	5.0	14.8	40.4	3.2
24086	38	0.7838	18	0.0	-0.2	12	-10.1	5.4	14.6	41.5	3.3
24086	36	0.7838	16	0.1	-0.3						
24086	34	0.7835	14	-0.3	0.0						
24086	32	0.7834	12	-0.4	-0.1						
24086	30	0.7844	9	-0.4	-0.1						
24086	28	0.7852	7	-0.1	0.2						
24086	26	0.7851	5	0.7	-0.1						
24086	24	0.7827	3	1.2	0.0						
24086	22	0.7830									
24086	20	0.7853									
24086	18	0.7859									
24086	16	0.7868									
24086	14	0.7882									
24086	12	0.7879									
24086	10	0.7870									
24086	8	0.7862									
24086	6	0.7868									
24086	4	0.7880									
24086	2	0.7813									

24086	0	0.7714									
24087	44	0.7349	44	0.8	0.0	-4	-6.9	4.3	11.1	29.6	3.4
24087	42	0.7355	41	-0.1	-0.3	3	-7.2	4.4	11.5	29.6	3.5
24087	40	0.7353	37	-0.6	0.0	8	-7.1	4.4	11.3	31.4	3.3
24087	38	0.7349	33	-1.2	-0.5	14	-7.1	4.4	12.7	36.2	3.3
24087	36	0.7350	29	-1.7	-0.1	18	-7.9	4.7	12.2	35.4	3.4
24087	34	0.7350	25	-2.1	-0.3	22	-9.7	5.2	11.3	30.4	3.5
24087	32	0.7349	21	-2.2	-0.1	26	-10.1	5.1	11.6	31.5	3.4
24087	30	0.7348	16	-2.2	-0.1	30	-10.1	5.1	12.2	35.8	3.4
24087	28	0.7345	11	-1.2	-0.3	34	-10.2	5.1	13.3	38.5	3.4
24087	26	0.7350	7	-0.3	-0.3	38	-9.4	5.0	11.9	34.9	3.4
24087	24	0.7336	3	0.9	-0.3	41	-9.0	5.0	12.0	35.1	3.4
24087	22	0.7359				44	-8.4	5.0	11.4	34.6	3.5
24087	20	0.7354									
24087	18	0.7357									
24087	16	0.7342									
24087	14	0.7340									
24087	12	0.7338									
24087	10	0.7333									
24087	8	0.7325									
24087	6	0.7354									
24087	4	0.7345									
24087	2	0.7356									
24087	0	0.7353									
24088	42	0.7272	44	1.8	-0.4	4	-7.1	5.4	13.1	29.3	3.2
24088	40	0.7347	41	2.4	-0.2	8	-7.1	5.4	12.4	30.2	3.2
24088	38	0.7301	37	1.9	-0.4	12	-6.7	5.4	12.2	30.1	3.2
24088	36	0.7273	33	2.1	-0.2	16	-6.3	5.7	12.1	29.3	3.3
24088	34	0.7247	29	2.1	-0.3	20	-6.1	6.1	13.2	37.2	3.3
24088	32	0.7247	25	1.9	-0.2	24	-6.6	5.9	4.5	18.2	3.4
24088	30	0.7259	21	2.1	-0.2	28	-5.6	5.5	15.1	41.8	3.2

24088	28	0.7280	16	1.9	-0.2	32	-5.4	5.6	14.8	41.2	3.2
24088	26	0.7259	11	1.7	-0.3	36	-5.8	6.0	15.5	42.9	3.2
24088	24	0.7254	7	2.1	-0.6	40	-5.5	6.2	14.6	41.2	3.3
24088	22	0.7362	5	2.2	-0.1						
24088	20	0.7251	3	2.4	-0.3						
24088	18	0.7269	1	2.4	-0.3						
24088	16	0.7224									
24088	14	0.7231									
24088	12	0.7287									
24088	10	0.7370									
24088	8	0.7247									
24088	6	0.7237									
24088	4	0.7262									
24088	2	0.7242									
24088	0	0.7350									
24089	44	0.7315	44	-0.4	-1.0	-25	-7.9	6.0	13.5	38.3	3.3
24089	42	0.7306	41	0.1	-0.9	-20	-9.6	5.9	13.7	39.2	3.3
24089	40	0.7317	37	0.4	-1.5	-15	-9.6	5.6	13.5	38.6	3.3
24089	38	0.7309	33	0.4	-3.9	-10	-8.6	5.3	13.1	36.8	3.3
24089	36	0.7308	29	0.7	-2.1	-5	-8.4	5.6	13.0	37.8	3.4
24089	34	0.7318	25	0.2	-2.0	5	-8.8	6.0	12.4	36.3	3.4
24089	32	0.7310	21	-0.2	-3.2	10	-9.1	5.8	14.5	40.9	3.3
24089	30	0.7311	16	-0.3	-1.5	15	-9.1	5.7	14.1	40.3	3.3
24089	28	0.7311	11	-0.7	-1.3	20	-9.1	6.0	14.1	40.1	3.3
24089	26	0.7332	7	-1.0	-0.5	25	-9.0	5.9	15.1	43.0	3.3
24089	24	0.7317	4	-1.3	-0.3	30	-9.0	6.1	14.4	40.5	3.3
24089	22	0.7308	2	-1.5	-0.1	35	-8.9	6.2	14.1	40.2	3.3
24089	20	0.7306	0	-1.4	-0.2	40	-8.7	6.3	13.9	39.6	3.3
24089	18	0.7316									
24089	16	0.7315									
24089	14	0.7314									

24089	12	0.7313									
24089	10	0.7337									
24089	8	0.7317									
24089	6	0.7379									
24089	4	0.7373									
24089	2	0.7353									
24089	0	0.7527									
24090	46	0.7445	44	-2.0	-1.4	-20	-12.6	7.6	12.4	34.7	3.3
24090	44	0.7447	41	-2.5	0.7	-17	-10.4	7.1	15.2	41.7	3.2
24090	42	0.7425	37	-2.5	0.8	-14	-9.9	7.0	14.8	40.4	3.2
24090	40	0.7379	33	-2.5	1.8	-11	-9.7	7.3	14.7	40.1	3.2
24090	38	0.7368	29	-2.4	0.3	-7	-10.1	7.5	14.8	40.6	3.2
24090	36	0.7374	25	-2.4	1.1	-3	-10.2	7.5	14.4	39.6	3.2
24090	34	0.7360	21	-2.4	0.9	4	-10.5	7.5	14.3	39.3	3.2
24090	32	0.7354	16	-2.5	1.2	10	-10.3	7.4	14.7	40.4	3.2
24090	30	0.7351	11	-2.1	0.5	14	-10.3	7.4	14.6	40.0	3.2
24090	28	0.7375	7	-2.3	1.1	18	-10.4	7.5	14.4	39.4	3.2
24090	26	0.7348	4	-2.3	1.0	22	-9.7	7.4	14.7	40.3	3.2
24090	24	0.7352	2	-2.1	2.4	26	-9.3	7.5	14.2	38.7	3.2
24090	22	0.7348				39	-11.1	7.7	6.1	43.5	3.6
24090	20	0.7346				32	-8.2	7.6	13.9	38.0	3.2
24090	18	0.7345				37	-8.2	7.5	13.7	37.6	3.2
24090	16	0.7343				40	-8.5	8.1	14.3	39.4	3.2
24090	14	0.7334									
24090	12	0.7342									
24090	10	0.7331									
24090	8	0.7329									
24090	6	0.7333									
24090	4	0.7331									
24090	2	0.7334									
24090	0	0.7352									

24091	40	0.7167	44	1.4	1.7	-10	-8.1	5.2	11.1	31.7	3.3
24091	38	0.7138	41	1.5	0.6	-5	-8.1	5.2	13.7	38.9	3.3
24091	36	0.7147	37	1.5	2.2	5	-8.1	4.9	13.7	38.7	3.3
24091	34	0.7181	33	1.3	1.7	10	-7.9	5.0	14.1	39.7	3.3
24091	32	0.7187	29	1.3	1.7	15	-7.8	4.8	14.0	39.7	3.3
24091	30	0.7251	25	1.4	0.6	20	-7.3	4.9	13.3	37.8	3.3
24091	28	0.7227	21	1.1	1.1	24	-7.2	4.9	14.1	39.7	3.3
24091	26	0.7253	16	0.7	-0.6	28	-7.2	4.8	14.0	39.7	3.3
24091	24	0.7227	11	0.7	1.0	32	-7.0	4.9	13.3	37.8	3.3
24091	22	0.7229	7	0.6	-0.2						
24091	20	0.7217	4	0.6	0.2						
24091	18	0.7252	2	0.7	-0.3						
24091	16	0.7232	0	0.7	-0.5						
24091	14	0.7253									
24091	12	0.7242									
24091	10	0.7246									
24091	8	0.7234									
24091	6	0.7200									
24091	4	0.7209									
24091	2	0.7223									
24091	0	0.7165									
24092	42	0.7268	44	2.7	-1.5	-20	-7.0	5.2	14.4	39.9	3.2
24092	40	0.7290	41	2.8	-0.6	-17	-7.3	5.3	14.6	39.8	3.2
24092	38	0.7287	37	2.8	0.1	-13	-7.9	5.4	15.2	42.4	3.3
24092	36	0.7305	33	2.8	0.1	-10	-7.3	5.1	14.8	41.8	3.3
24092	34	0.7280	29	2.5	0.3	-8	-7.0	5.3	14.3	39.0	3.2
24092	32	0.7265	25	2.4	-0.2	-4	-6.9	5.4	15.0	40.7	3.2
24092	30	0.7263	21	2.3	-0.8	7	-7.8	5.9	14.6	40.3	3.2
24092	28	0.7245	16	2.4	-0.8	16	-7.5	5.9	14.9	40.5	3.2
24092	26	0.7297	11	2.3	-0.3	23	-7.3	6.0	14.9	41.8	3.3
24092	24	0.7270	7	2.0	-0.5	30	-6.6	5.7	14.7	39.7	3.2

24092	22	0.7255	3	2.0	-0.9	37	-6.4	5.8	14.8	40.1	3.2
24092	20	0.7263	0	1.8	-2.9	44	-6.1	5.8	14.7	39.8	3.1
24092	18	0.7294									
24092	16	0.7263									
24092	14	0.7295									
24092	12	0.7341									
24092	10	0.7261									
24092	8	0.7261									
24092	6	0.7268									
24092	4	0.7295									
24092	2	0.7320									
24092	0	0.7293									
24093	38	0.7422	44	1.9	-4.7	-16	-6.7	4.3	15.5	44.1	3.3
24093	36	0.7417	41	2.5	-2.6	-12	-6.4	5.8	15.3	42.9	3.3
24093	34	0.7410	37	2.5	-3.2	-8	-7.8	5.4	15.8	43.9	3.2
24093	32	0.7397	33	2.4	-2.8	-4	-7.2	5.2	15.9	44.3	3.3
24093	30	0.7398	29	2.4	-4.0	0	-6.3	5.0	15.6	43.4	3.2
24093	28	0.7478	25	2.2	-0.7	4	-6.2	5.5	15.8	44.0	3.3
24093	26	0.7388	21	2.1	-1.7	8	-6.9	5.9	15.6	43.4	3.2
24093	24	0.7382	16	2.2	-2.4	12	-6.4	5.7	15.8	43.4	3.2
24093	22	0.7380	11	1.9	-0.9	16	-6.6	6.0	15.8	43.8	3.2
24093	20	0.7515	7	2.1	-3.1	20	-7.6	5.4	15.6	43.5	3.3
24093	18	0.7362	3	2.2	-3.3						
24093	16	0.7361									
24093	14	0.7522									
24093	12	0.7515									
24093	10	0.7516									
24093	8	0.7489									
24093	6	0.7472									
24093	4	0.7323									
24093	2	0.7346									

24093	0	0.7528									
24094	36	0.7426	42	0.4	-0.5	10	-11.9	6.6	11.2	32.5	3.3
24094	34	0.7425	40	0.5	0.3	14	-11.3	6.9	12.1	29.2	3.4
24094	32	0.7458	36	0.5	-1.4	18	-10.8	6.5	14.1	39.7	3.3
24094	30	0.7418	34	0.6	0.9	22	-9.9	6.5	12.9	37.1	3.3
24094	28	0.7408	32	0.2	-1.0	26	-9.2	6.4	11.1	32.0	3.4
24094	26	0.7406	28	0.0	0.5	30	-9.1	6.4	11.0	28.4	3.4
24094	24	0.7411	24	-0.7	0.4	34	-8.7	6.9	13.7	38.4	3.3
24094	22	0.7415	20	-1.2	0.4	38	-8.8	6.9	14.2	40.1	3.3
24094	20	0.7411	16	-1.7	0.1	42	-8.7	6.9	14.3	39.9	3.3
24094	18	0.7424	14	-2.4	-1.1	46	-8.7	6.7	13.9	39.5	3.3
24094	16	0.7420	11	-2.6	0.0						
24094	14	0.7431	9	-2.9	-2.0						
24094	12	0.7423									
24094	10	0.7415									
24094	8	0.7453									
24094	6	0.7470									
24094	4	0.7469									
24094	2	0.7475									
24094	0	0.7479									
24095	50	0.7320	41	1.6	0.4	-14	-7.5	6.0	14.0	35.0	2.9
24095	48	0.7271	38	1.6	-4.1	-10	-7.5	6.1	14.7	37.2	2.9
24095	46	0.7266	35	1.7	-1.8	-6	-7.5	6.0	13.4	34.0	2.9
24095	44	0.7290	32	1.8	0.4	-2	-7.5	5.8	14.1	35.5	2.9
24095	42	0.7302	29	1.7	0.6	2	-7.2	5.5	14.5	37.6	3.0
24095	40	0.7296	25	2.0	-1.6	6	-7.2	5.2	13.7	34.9	3.0
24095	38	0.7322	21	1.7	-0.6	9	-6.8	5.2	17.0	6.5	3.8
24095	36	0.7329	18	1.7	-4.1	13	-8.0	4.9	8.3	2.9	3.4
24095	34	0.7337	15	1.8	-1.8	19	-8.1	5.1	10.4	3.8	3.4
24095	32	0.734	12	1.2	-2.6	24	-7.6	5.2	11.5	4.3	3.2
24095	30	0.7334	10	1.6	-2.1	29	-8.4	5.6	17.4	6.4	3.1

24095	28	0.7331	5	0.9	-1.8						
24095	26	0.7340	3	0.7	-1.3						
24095	24	0.7325									
24095	22	0.7317									
24095	20	0.7318									
24095	18	0.7313									
24095	16	0.7293									
24095	14	0.7313									
24095	12	0.7320									
24095	10	0.7338									
24095	8	0.7334									
24095	6	0.7381									
24095	4	0.7343									
24095	2	0.7351									
24095	0	0.7344									
24096	44	0.7355	44	1.3		8	-6.8	4.8	11.5	28.4	3.5
24096	42	0.7341	41	1.3		12	-6.9	5.3	12.3	37.2	3.5
24096	40	0.7346	38	1.3		16	-6.5	6.7	12.2	35.7	3.4
24096	38	0.7331	35	1.3		20	-6.8	7.1	12.7	38.4	3.5
24096	36	0.7338	32	1.3		24	-6.3	7.0	14.2	39.8	3.3
24096	34	0.7345	27	1.4							
24096	32	0.7335	23	1.4							
24096	30	0.7329	19	1.4							
24096	28	0.7323	16	1.4							
24096	26	0.7322	12	1.4							
24096	24	0.7318	9	1.3							
24096	22	0.7328	6	1.3							
24096	20	0.7326	2	1.3							
24096	18	0.7351									
24096	16	0.7307									
24096	14	0.7405									

24096	12	0.7311									
24096	10	0.7303									
24096	8	0.7317									
24096	6	0.7392									
24096	4	0.7380									
24096	2	0.7325									
24096	0	0.7327									
24097	44	0.7326	44	0.6	-2.9	-21	-6.8	6.4	14.9	41.5	3.3
24097	42	0.7316	41	0.3	-1.2	-18	-6.7	6.2	15.4	42.8	3.2
24097	40	0.7317	37	0.5	-3.8	-15	-7.4	5.2	15.2	42.1	3.2
24097	38	0.7323	33	0.6	-0.3	-12	-7.7	4.3	12.2	28.4	3.3
24097	36	0.7307	29	0.8	-0.5	-9	-7.3	4.2	12.4	28.0	3.2
24097	34	0.7313	25	0.9	-1.0	-6	-7.7	4.3	10.1	28.3	3.2
24097	32	0.7303	21	1.1	-1.1	-3	-7.3	4.2	10.0	27.9	3.2
24097	30	0.7300	16	1.1	-1.3	4	-8.5	4.7	12.2	35.7	3.4
24097	28	0.7289	11	1.3	-1.9	8	-8.6	4.7	6.1	17.5	3.3
24097	26	0.7289	7	1.3	-1.3	12	-8.2	4.7	8.6	24.0	3.2
24097	24	0.7292	3	1.2	-1.1	16	-7.5	5.0	11.0	26.2	3.3
24097	22	0.7293	0	1.3	-1.3	20	-8.0	6.3	11.1	27.2	3.3
24097	20	0.7298				24	-7.3	6.3	13.2	36.9	3.3
24097	18	0.7306				28	-7.0	6.4	14.8	41.3	3.3
24097	16	0.7291				32	-7.2	5.8	12.4	34.0	3.2
24097	14	0.7283				36	-7.2	5.7	15.3	41.6	3.2
24097	12	0.7283				40	-7.0	6.1	15.2	42.2	3.2
24097	10	0.7288									
24097	8	0.7282									
24097	6	0.7286									
24097	4	0.7292									
24097	2	0.7287									
24097	0	0.7295									
24098	54	0.7338	44	1.5	3.2	-18	-7.2	5.1	14.2	40.2	3.3

24098	52	0.739	41	1.6	3.3	-15	-6.9	4.7	14.8	41.5	3.3
24098	50	0.7405	37	1.5	3.4	-12	-7.0	4.8	14.7	41.3	3.3
24098	48	0.7443	33	1.4	0.6	-9	-7.5	4.6	12.5	34.9	3.2
24098	46	0.7455	29	1.2	1.4	-6	-7.3	4.6	13.2	37.2	3.3
24098	44	0.7455	25	1.3	2.5	-3	-9.2	5.3	9.1	21.9	3.7
24098	42	0.744	21	1.6	2.6	4	-7.1	4.8	11.1	27.1	3.3
24098	40	0.7435	16	1.4	2.3	6	-7.2	4.8	11.1	30.1	3.3
24098	38	0.7423	11	2.0	1.8	8	-7.3	4.8	12.2	35.0	3.2
24098	36	0.7441	7	1.8	1.6	12	-6.9	4.7	16.1	44.5	3.2
24098	34	0.7436	5	1.8	0.9	24	-8.1	5.1	11.4	33.3	3.4
24098	32	0.7471	3	1.8	0.3	28	-7.7	5.8	11.4	33.3	3.4
24098	30	0.7436	1	1.9	-3.5	32	-7.5	5.8	12.8	37.2	3.4
24098	28	0.7426				36	-7.8	6.1	15.1	42.2	3.3
24098	26	0.7450				40	-7.7	5.5	14.6	41.1	3.3
24098	24	0.7478									
24098	22	0.7491									
24098	20	0.7512									
24098	18	0.7529									
24098	16	0.7582									
24098	14	0.7612									
24098	12	0.7567									
24098	10	0.7580									
24098	8	0.7555									
24098	6	0.7534									
24098	4	0.7556									
24098	2	0.7582									
24098	0	0.7573									
24099	46	0.7387	44	2.6	-1.1	-14	-8.0	4.7	13.2	37.4	3.3
24099	44	0.7387	41	2.5	-0.9	-11	-7.5	4.7	13.9	38.6	3.2
24099	42	0.7358	37	2.4	-1.6	-10	-7.4	4.6	13.4	37.8	3.3
24099	40	0.7359	33	2.4	-0.4	-6	-7.1	4.7	12.8	36.3	3.3

24099	38	0.7365	29	2.4	0.6	-3	-7.0	4.6	12.8	36.5	3.3
24099	36	0.7375	25	2.3	1.1	4	-7.1	4.6	11.4	33.8	3.5
24099	34	0.7381	21	2.4	-1.0	8	-7.4	4.8	11.4	33.7	3.4
24099	32	0.7367	16	2.4	2.3	12	-6.6	4.5	12.3	35.6	3.4
24099	30	0.7368	11	2.3	1.3	16	-6.5	4.4	12.2	35.3	3.4
24099	28	0.7386	9	2.2	-1.1	20	-6.6	4.4	12.6	36.0	3.3
24099	26	0.7381	7	2.5	2.2	24	-6.5	4.5	12.9	37.1	3.3
24099	24	0.7377	5	2.4	0.8	28	-6.2	4.5	12.5	35.6	3.3
24099	22	0.7395	3	2.7	-0.2	32	-6.2	4.5	13.2	37.1	3.3
24099	20	0.7364	1	2.9	-0.6	36	-5.7	4.5	13.7	38.4	3.3
24099	18	0.7359				40	-6.0	4.6	13.0	36.9	3.3
24099	16	0.7356									
24099	14	0.7351									
24099	12	0.7353									
24099	10	0.7352									
24099	8	0.7356									
24099	6	0.7352									
24099	4	0.7346									
24099	2	0.7383									
24099	0	0.7354									
24100	32	0.7456	31	1.6	-0.7	-21	-7.9	4.2	13.4	37.2	3.2
24100	30	0.7461	29	1.4	0.8	-18	-7.8	4.3	14.3	39.4	3.2
24100	28	0.7468	27	1.0	-0.3	-15	-7.2	4.4	14.4	39.5	3.2
24100	26	0.7462	24	0.9	-1.1	-11	-6.9	4.3	14.3	39.5	3.2
24100	24	0.7450	21	0.5	-1.8	-7	-6.5	4.2	14.4	39.5	3.2
24100	22	0.7455	18	0.4	-0.7	-3	-6.9	4.1	14.6	40.0	3.2
24100	20	0.7481	16	0.3	0.5	4	-7.3	4.4	15.0	41.0	3.2
24100	18	0.7455	14	0.0	-0.6	8	-8.0	4.7	14.5	39.9	3.2
24100	16	0.7465	11	0.0	-1.2	12	-8.2	4.7	14.6	40.0	3.2
24100	14	0.7442	9	0.3	-1.5	15	-8.4	4.9	14.5	39.7	3.2
24100	12	0.7429	6	0.3	0.0	18	-8.1	4.9	14.5	39.8	3.2

24100	10	0.7425	4	0.4	-1.0	21	-8.1	5.0	14.5	39.6	3.2
24100	8	0.7425	1	0.3	0.5	24	-7.9	5.7	14.5	40,0	3.2
24100	6	0.7422				27	-6.6	6.0	14.5	39.8	3.2
24100	4	0.7429				31	-6.8	6.7	14.4	39.8	3.2
24100	2	0.7453				36	-7.1	7.2	14.3	39.9	3.2
24100	0	0.7411									
24101	50	0.7283	48	1.3		-15	-6.5	4.3	15.9	44.6	3.3
24101	48	0.7276	44	1.3		-12	-6.1	4.3	15.2	45.0	3.3
24101	46	0.7217	43	1.3		-8	-5.9	4.2	15.7	43.8	3.3
24101	44	0.7213	39	1.2		-4	-5.8	4.0	15.5	43.5	3.3
24101	42	0.7243	36	1.2		3	-6.5	4.5	15.4	44.6	3.3
24101	40	0.7168	33	1.3		6	-7.1	4.6	15.2	44.1	3.2
24101	38	0.7182	27	1.2		9	-7.2	4.7	15.3	44.3	3.2
24101	36	0.7202	24	1.2		12	-7.2	4.8	15.3	44.1	3.2
24101	34	0.7212	20	1.2		15	-7.2	5.2	11.6	32.3	3.2
24101	32	0.7262	15	1.1		18	-7.2	5.1	15.1	44.4	3.2
24101	30	0.7210	9	1.2		21	-7.0	5.3	15.2	44.8	3.2
24101	28	0.7191	5	1.3		24	-6.9	5.4	15.7	44.2	3.2
24101	26	0.7187	2	1.3		27	-6.9	5.4	15.3	44.5	3.3
24101	24	0.7224				30	-7.1	5.5	15.2	44.5	3.2
24101	22	0.7242				33	-7.0	5.7	15.6	44.7	3.2
24101	20	0.7284				36	-7.1	6.0	15.3	44.7	3.2
24101	18	0.7243				39	-7.3	6.1	15.2	44.3	3.2
24101	16	0.7286				42	-7.4	6.2	15.3	44.2	3.3
24101	14	0.7264				45	-7.4	6.3	15.3	43.9	3.2
24101	12	0.7257				48	-7.5	6.4	15.3	43.8	3.2
24101	10	0.7303									
24101	8	0.7245									
24101	6	0.7262									
24101	4	0.7217									
24101	2	0.7213									

24101	0	0.7196									
24102	52	0.7312	52	1.1		-10	-7.1	5.9	15.3	42.5	3.2
24102	50	0.7303	50	1.2		-6	-7.4	6.0	15.2	44.9	3.2
24102	48	0.7286	48	1.2		-2	-7.6	6.2	14.6	40.2	3.2
24102	46	0.7286	44	1.1		5	-7.8	6.4	14.9	40.9	3.2
24102	44	0.7283	43	1.3		10	-7.7	6.7	15.1	41.7	3.2
24102	42	0.7284	39	1.3		14	-7.3	6.8	15,0	41.3	3.2
24102	40	0.7267	36	1.4		18	-7.4	6.7	15.3	41.9	3.2
24102	38	0.7275	33	1.3		22	-6.7	6.8	15,0	42.2	3.3
24102	36	0.7276	27	1.2		28	-7.2	6.7	15.1	44.5	3.2
24102	34	0.7272	24	1.3		33	-7.1	6.9	14.7	41.1	3.3
24102	32	0.7269	20	1.2							
24102	30	0.7287	15	1.2							
24102	28	0.7278	9	1.2							
24102	26	0.7285	5	1.3							
24102	24	0.7279	2	1.1							
24102	22	0.7274									
24102	20	0.7276									
24102	18	0.7282									
24102	16	0.7281									
24102	14	0.7274									
24102	12	0.7285									
24102	10	0.7270									
24102	8	0.7273									
24102	6	0.7274									
24102	4	0.7285									
24102	2	0.7289									
24102	0	0.7290									

Appendix 4: All isotopic data for modern tooth dentine serial samples.

Tooth number	Mm from ERJ	$\delta^{15}N$ (‰)	$\delta^{13}C$ (‰)	%N	%C	C:N ratio (atomic)
24144	-25	8.9	-7.9	15.0	45.0	3.4
24144	-23	8.2	-8.0	14.6	44.8	3.5
24144	-20	7.7	-7.8	14.7	44.7	3.5
24144	-18	7.9	-7.8	14.7	45.0	3.5
24144	-15	6.8	-6.8	15.1	46.4	3.5
24144	-12	6.5	-6.6	15.7	45.9	3.4
24144	-9	7.3	-6.4	15.3	44.7	3.4
24144	-6	7.6	-7.2	14.7	43.8	3.4
24144	-3	7.6	-8.5	12.3	36.2	3.4
24144	0	7.2	-7.5	15.1	42.9	3.3
24144	3	7.0	-8.1	15.0	45.2	3.5
24144	7	6.6	-7.0	14.8	43.5	3.4
24144	11	6.5	-7.2	15.0	43.8	3.4
24144	15	6.8	-7.3	15.0	43.4	3.3
24144	18	7.6	-7.4	14.8	42.7	3.3
24144	21	7.0	-7.6	14.8	42.3	3.3
24144	24	6.7	-7.4	15.3	43.7	3.3
24144	27	8.4	-6.8	14.9	42.8	3.3
24144	30	7.3	-7.0	14.8	43.9	3.4
24144	33	6.9	-7.0	15.3	43.4	3.3
24142	-15	8.6	-8.7	14.4	44.7	3.4
24142	-12	7.8	-7.8	14.3	43.9	3.4
24142	-9	7.5	-7.5	14.9	44.7	3.4
24142	-6	7.1	-8.2	14.6	43.4	3.4
24142	-3	7.9	-7.8	14.5	42.9	3.4
24142	1	7.4	-7.3	14.7	43.2	3.4
24142	5	6.5	-7.2	15.1	46.2	3.4
24142	9	6.6	-6.8	15.4	44.8	3.3
24142	13	6.5	-6.8	15.1	43.2	3.3
24142	17	7.0	-7.6	14.7	43.2	3.4
24142	21	6.8	-7.8	14.2	43.5	3.4
24142	25	9.8	-9.0	14.3	45.5	3.4
24143	-23	7.7	-9.0	14.6	40.6	3.2
24143	-21	8.5	-7.8	15.0	39.9	3.1
24143	-18	7.6	-8.2	14.6	40.0	3.1
24143	-15	7.5	-8.2	14.8	41.9	3.3
24143	-12	7.8	-8.0	14.8	40.4	3.1
24143	-9	7.7	-7.8	15.1	40.5	3.1
24143	-6	7.6	-8.3	15.3	41.0	3.1
24143	-3	8.1	-8.3	15.1	40.7	3.1

24143	1	7.9	-10.1	13.1	44.3	3.1
24143	3	6.4	-7.2	14.8	40.7	3.2
24143	7	8.6	-8.7	13.9	41.6	3.4
24143	11	8.7	-8.0	14.5	39.6	3.1
24143	15	9.0	-7.6	14.7	38.6	3.0
24143	19	7.4	-7.2	15.0	40.3	3.1
24143	25	9.0	-8.0	14.9	39.6	3.0
24143	30	9.3	-7.9	13.9	36.1	3.0
24143	34	9.5	-8.1	15.0	39.8	3.0
24143	37	8.9	-8.4	11.9	32.4	3.1
24143	40	9.3	-7.9	14.2	38.4	3.1